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THE JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY

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REVIEWS

LONDON
ROYAL AERONAUTICAL SOCIETY, 4 HAMILTON PLACE, W.1

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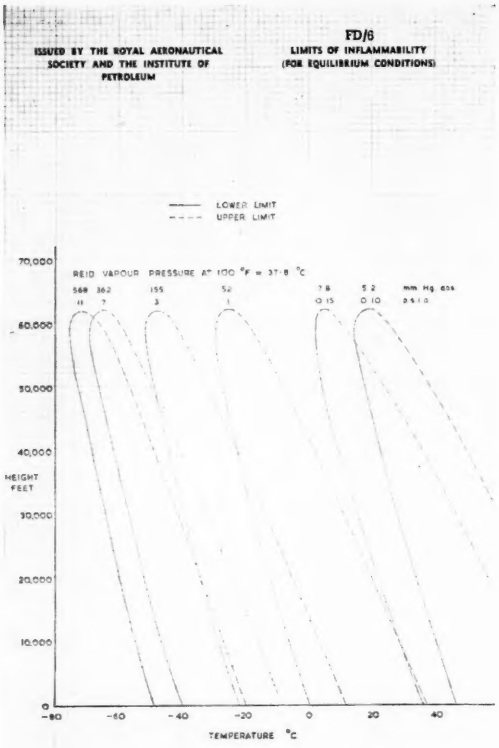

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THE ROYAL AERONAUTICAL SOCIETY

4 HAMILTON PLACE LONDON W1

Secretary's News Letter

JANUARY 1952

A MESSAGE FROM THE PRESIDENT

WHEN I took office as President of the Society last May I looked forward with great pleasure to the opportunity I should have of meeting so many members personally, during the Session, at lectures and other functions. This pleasure has been denied me lately through a period of ill-health, and I more than welcome this opportunity of sending a word to you all.

I have watched with great interest the increased activities of the Branches, and I do regret my inability up to the present to visit them.

The Anglo-American Conference in September provided a very strenuous period for everyone, but I think all will agree with me that it was well worth it. I personally feel it was so, both technically and socially.

Since the Conference there have been fourteen lectures before members of the Society and four Council meetings, at which the Vice-Presidents have ably deputised for me and I am very grateful to them.

We still have the Spring Session of Lectures to which we may look forward and, of course, the Louis Bleriot Lecture in Paris in March. I very much hope to be with you on these occasions.

Again looking ahead, I should like members to know that the Council and the Future Policy Committee are strenuously exploring the Society's future activities and fields of usefulness to our members in particular and the aeronautical community at large.

The fruition of the many schemes of technical work and publications which we envisage is admittedly somewhat retarded by the difficulty in obtaining suitable technical staff.

We are, at the moment, exploring the organisation of reciprocal research Fellowships in this country and abroad.

Another branch of the Society's work which is being carefully reviewed is the increased facilities of the Library.

One final point; I would like to draw members' attention to the help the Staff of the Society can give them, as and when they are asked, and I hope that members will not hesitate to call on the Secretary and his Staff for any assistance they may require.

May I wish you all a very happy, peaceful and prosperous New Year.

President.

NOTICES

CONTENTS OF JANUARY JOURNAL

Power Controls for Aircraft, C. F. Joy, A.F.R.Ae.S.

Some Aspects of Aircraft Design and Manufacture for Limited Production, W. S. Hollyhock, A.F.R.Ae.S.

Aircraft in Agriculture, P. H. Southwell.

The Application of Plastics to Aircraft, R. A. R. Black, B.Sc., B.A.

Reviews.

(An annual sum of £250 is available for premium awards for papers published in the Journal. These premium awards average 15 guineas each. Members and non-members of the Society are invited to submit papers on any aspect of aeronautics.)

THE AERONAUTICAL QUARTERLY—Part III, Volume III

Part III, November 1951 of the Aeronautical Quarterly is now available. The Contents of Part III, Volume III are:—

Photoelasticity and Aircraft Design	H. T. Jessop and C. Snell
A Note on the Design of Ducted Fans	B. Thwaites
A New Treatment of the Tuned Absorber with Damping ...	D. C. Johnson
A New Approach to Thin Aerofoil Theory	M. J. Lighthill
The Profile Drag of Yawed Wings of Infinite Span ...	A. D. Young and T. B. Booth
Beams on Cross-Girders with Clamped Ends	J. M. Klitchieff
A Direct Aerodynamic Proof of the Biot-Savart Law ...	J. Lockwood Taylor

Copies of Volume III, Parts I and II, are still available from the offices of the Society at 7s. 9d. a copy to members of the Society, post paid, or 10s. 3d. to non-members, post paid.

After four years as Civil Air Attaché at the British Embassy, Washington, Group Captain Christopher Clarkson, A.F.C., M.I.A.S., *Associate Fellow*, will hand over to his successor, Mr. R. S. S. Dickinson, on the 31st January 1952. Group Captain Clarkson's plans for the future are uncertain at present, but he expects to return to New York, at least for the time being.

DIARY

LONDON.

January 22nd
GRADUATES' AND STUDENTS' SECTION—Aircraft in Agriculture, P. H. Southwell. 4 Hamilton Place. 7.30 p.m.

January 31st
SECTION LECTURE—The Problem of Short Haul Air Transport, P. W. Brooks. 4 Hamilton Place. 7 p.m.

February 7th
MAIN LECTURE—The Availability and Use of Aeronautical Information. A Joint Discussion with the Aeronautical Information Group of A.S.L.I.B. Led by A. A. Hall Institution of Civil Engineers, Great George Street. 6 p.m.

February 12th
SECTION LECTURE—Flight Test Problems for Civil Aircraft, B. P. Laight. 4 Hamilton Place. 7. p.m.

February 14th
GRADUATES' AND STUDENTS' SECTION—Radar. A lecture illustrated by films, B. W. Hodlin. 4 Hamilton Place. 7.30 p.m.

BRANCHES.

January 14th
Bristol—Fatigue—Its Effect on Engine Design, K. Chamberlain. Filton House. 6 p.m.

January 15th
Belfast—Aeronautical Brains Trust: Rear Admiral M. S. Slattery, G. T. R. Hill, J. L. Parker, A. W. S. Clarke, A. Vines, Capt. J. L. Pritchard. College of Technology. 7 p.m.

January 16th
Coventry—Rocket Propelled Missiles, W. H. Stephens. The Wine Lodge. 7.30 p.m.
Southampton—The Korean Campaign, W. Courtenay. University College. 7 p.m.

January 17th
Isle of Wight—Metal Adhesive Processes, F. H. Parker. Saunders-Roe Club House, E. Cowes. 6 p.m.
Manchester—Power Controls, D. J. Millard. College of Technology. 7.30 p.m.
Portsmouth—FILMS. Airspeed Ltd. The Airport. 6 p.m.
Yeovil—FILMS. Westland Aircraft Co. Ltd.

January 23rd
Bristol—Flight Refuelling, C. H. Latimer-Needham. Filton House. 6 p.m.
Brough—Planning and Production Methods used for the D.H. Comet, H. Povey. Electricity Showrooms, Ferensway, Hull. 7.30 p.m.

January 30th
Gloucester and Cheltenham—Turbo-Props, E. Danvers. Wheatstone Hall, Gloucester. 7.30 p.m.
Weybridge—Junior Prize Lecture. Vickers-Armstrongs Ltd. 6 p.m.

January 31st
Isle of Wight—Electronics, P. Jackson. Saunders-Roe Club House, E. Cowes. 6 p.m.
Portsmouth—Airline Operating Problems, P. G. Masefield. Airspeed Ltd., The Airport. 6 p.m.

February 4th
Derby—Airships, Lord Ventry. Rolls-Royce Welfare Hall. 6.15 p.m.

February 6th
Chester—Members' Lectures. Grosvenor Hotel. 7.30 p.m.

February 11th
Bristol—The Design of a Jet Engine, A. A. Lombard. Filton House. 6 p.m.

February 13th
Manchester—Problems of Servicing Modern Aircraft, Group Captain G. M. Buxton. College of Technology. 7.30 p.m.

February 14th
Isle of Wight—Welded Magnesium Aircraft Components, R. J. Cross. Saunders-Roe Club House. E. Cowes. 6 p.m.
Portsmouth—FILMS. Airspeed Ltd., The Airport. 6 p.m.

MEMBERS' NEW APPOINTMENTS

WING COMMANDER J. A. KENT (*Associate Fellow*) has been appointed Assistant to the Chief of Flight Test Division, Wright Air Development Centre, Wright-Patterson Air Force Base, U.S.A. He was formerly Chief of the Fifth Phase Test Branch in the All Weather Section of Flight Test Division.

MR. C. B. V. NEILSON (*Associate Fellow*) has recently been appointed to the Board as Technical Director of Electro-Hydraulics Ltd. He joined the Company in 1943 as Chief Electrical Designer and has been Chief Designer (Aircraft) since 1946.

MR. T. P. SEARIGHT (*Fellow*) has resigned his position as Chairman of H. M. Hobson Ltd., but remains a Director.

MR. J. LANKESTER PARKER (*Fellow*) was installed as Master of the Guild of Air Pilots and Air Navigators of the British Empire by H.R.H. Princess Elizabeth on Friday, 7th December at the Mansion House. Mr. Lankester Parker was elected an Associate Fellow on 8th February 1927 and was elected a Fellow on 16th March 1944.

HONOURS RECEIVED BY MEMBERS

The honorary degree of Doctor of Science in Engineering of Bristol University was conferred on Mr. A. E. Russell (*Fellow*), Director and Chief Designer (Aircraft) of The Bristol Aeroplane Company Ltd., by the Prime Minister, Mr. Winston Churchill, *Honorary Fellow* of the Society, in a ceremony at the University on 14th December 1951.

INSTITUTE OF THE AERONAUTICAL SCIENCES

The Fifteenth Wright Brothers Lecture was read before the Institute of the Aeronautical Sciences by Dr. P. B. Walker, F.R.Ae.S., on "The Experimental Approach to Aircraft Structural Research" on 17th December 1951.

Mr. Wellwood E. Beall has been elected President of the Institute for 1952. The following are the four new Vice-Presidents of the Institute:—

Preston R. Bassett.
Smith J. De France.
Edward H. Heinemann.
John C. Leslie.

COMMITTEE MEETINGS HELD IN DECEMBER

During December five meetings were held by Committees of the Society. Outside bodies engaged in aircraft engineering and research held nine meetings in the offices of the Society.

THE INSTITUTION OF MECHANICAL ENGINEERS

Members of the Society are invited by the Institution of Mechanical Engineers to attend a meeting on Friday, 25th January 1952 at Storey's Gate, S.W.1, at which a paper on "The Marine Gas Turbine from the Viewpoint of an Aeronautical Engineer" will be presented by Mr. A. Holmes Fletcher, B.Sc. (Eng.), M.I.Mech.E. The meeting will begin at 5.30 p.m. and light refreshments will be served at 5.0 p.m.

Members are invited to take part in the Discussion following the paper or to submit comments in writing. Advance copies of the paper may be obtained from the Secretary, The Institution of Mechanical Engineers, Storeys Gate, London, S.W.1.

ASSOCIATE FELLOWSHIP EXAMINATION

Candidates for the May 1952 Associate Fellowship examination are reminded that all entry forms should be received by the Secretary by 31st January 1952. Entries from candidates abroad closed on 30th November.

JOURNAL BINDING

Members are reminded that a special leaflet on JOURNAL binding for the 1951 Volume and for 1952 was enclosed with the December JOURNAL. Copies of this leaflet are available on application to the Society.

ELECTIONS

The following is a list of new members and transfers of membership of the Society:—

Associate Fellows

Richard Cleminson Cussons
Douglas Dewar (*from Associate*)
Joseph Huston Gault (*from Graduate*)
William Rogers Hoskin (*from Graduate*)
Joseph Reginald Cyril Lane
Jack Harry London (*from Graduate*)
Zbigniew Olenski
Tom Smith (*from Associate*)
Basil McCall Wilson

Associates

Frank Henry Bonney
Guido Colm
Arthur William Cooper
Basil Frederick Dockree
Gerald Ray Wooll

Graduates

Raymond Francis Anderson
Henry Gordon Anthony (*ex-Student*)
Robert Goodwin Baylis
Thomas William Coombe
Robert John Gladwell (*from Student*)
Roger Anthony Grimston (*from Student*)
Gerald David Owen Humphreys
Godfrey Newby Lance
Ivor Leslie Kerr Rye (*from Student*)
Harold Warren Shattock
William John Taylor (*from Student*)
Jeffrey Tinkler (*from Student*)
James Peter Whitworth
Denys William Wright

Students

John Robert Andrews
Michael John Baker
Roy Budgen
Gabriel Nemethy
Edward Frederick Simmonds
Julian Wolkovitch

Companions

Ronald Montgomery Crawford
Reginald William Ward

ACKNOWLEDGMENT

The Council acknowledge with grateful thanks three volumes of the third edition of "Handbook of Aeronautics" from Group Captain F. A. Norton, C.B.E., M.Sc.

CHANGES OF ADDRESS

To assist in keeping the records of members correct and up to date the Secretary will be glad if all members will notify him as soon as possible of changes of address.

When notifying changes please give the following particulars:—

Name (in block letters).
Grade of membership.
New address (in block letters).
Old address.

Changes of address must be received *before the 15th of the month* in order to be effective for the JOURNAL for the following month.

ANNUAL SUBSCRIPTIONS

Members are reminded that their annual subscriptions became due on 1st January 1952. The rates are:—

	Home			Abroad		
	£	s.	d.	£	s.	d.
Fellows	5	5	0	4	4	0
Associate Fellows	4	4	0	3	3	0
*Associates	3	3	0	3	3	0
Graduates (aged under 26) ...	2	2	0	2	2	0
Graduates (aged 26 and over) ...	2	12	6	2	12	6
Students (aged under 21)	1	1	0	1	1	0
Students (aged 21 and over) ...	1	11	6	1	11	6
Companions	3	3	0	3	3	0
Founder Members	2	2	0	2	2	0

* Any Associate elected before 1st October 1947 may, if he wishes, elect not to receive the JOURNAL, and in this case his subscription will be reduced by £1 1s. 0d. to £2 2s. 0d.

It will avoid delay and confusion if members, when sending remittances for subscriptions, will state their names clearly and give their addresses and grades of membership.

Remittances should be made payable to the Royal Aeronautical Society.

*Power Controls for Aircraft**

by

C. F. JOY, A.F.R.Ae.S.

1. INTRODUCTION

In reviewing the various papers on power controls which have been read before the Society in the past few years, it soon became apparent that, considering the broad issues involved, there is little to add to what has already been said.

D. J. Lyons[1] admitted, somewhat reluctantly, that power controls might become a necessity on aircraft designed to fly for extended periods in the transonic region. He claimed that mere size does not, in itself, demand powered controls, since it should be possible to design aircraft up to 150 to 200 ft. wing span with spring tabs, and if aerodynamic servos are used, the size limit is likely to be well beyond 300 ft. span.

To the author's knowledge, neither of these statements has been disproved in the intervening period, and although there is now more evidence to suggest that power controls are desirable in the transonic region, it has not been shown conclusively that they are essential.

Both Lyons and A. E. Russell[2] emphasised the important advantage which power controls offer, in that the whole system can be tested thoroughly on a ground rig. This exchange of *ad hoc* testing, during those precious early flying hours (testing which invariably excludes all other work and results in extensive modifications to the control surfaces) for a systematic mechanical test of the whole flying control system on a ground rig *before* flight, results in valuable saving of flight test time. The force of this argument has been demonstrated on a number of aircraft during the past few years, notably the Brabazon and the Comet. There is little doubt that the Comet's fine record of 153 hours during the six months following the first flight, was largely due to the use of powered controls. Experience at Handley Page's also confirms that very little flying time is needed to get powered controls right.

The elimination of aerodynamic balance drag and mass-balance weight, made possible by the use of the "all power" flying control system, that is, with no feed back and no manual reversion, can make a considerable "virtue" of the necessity of fitting power controls, especially on long range aircraft.

Reliability is the word that comes into everyone's mind, when the subject of power controls is raised. Fear of unreliability is the one factor which, above all, encourages the aircraft designer to look somewhat longingly at aerodynamic balances, spring tabs, aerodynamic servos and all the other often troublesome gadgets, before he puts his trust into the electrical engineer, the hydraulic engineer, or perhaps the pneumatic engineer.

A number of aircraft have been flown with powered controls having no manual reversion for emergency and, so far as is known, there have been no failures resulting in catastrophic accidents.

Much work has been done on the mechanical side of such controls, including the development of various methods of detecting and rendering inoperative, automatically, the faulty half-unit of a duplicated actuator. This work has resulted in a high standard of reliability and the chance of complete failure is probably as remote as that of any other vital part of the aircraft.

During the past ten years or so, a number of aircraft have been fitted with power boost or power assistance, usually in the form of a simple hydraulic jack and follow-up gear, with proportional feed back. This well-known arrangement in which the actuator is virtually additional to a normal manual system, has generally given satisfactory service.

---

*A Section Lecture given on 9th October 1951. Mr. Joy is Assistant Chief Designer, Handley Page Ltd.

The foregoing summarises briefly the general position on powered flying controls. It is now proposed to examine in detail some of the factors affecting choice of a system, particularly for a new design on which the primary considerations are high speed and range/load performance.

2. GENERAL CONSIDERATIONS IN CHOOSING A POWER CONTROL SYSTEM

Because of the number of variables involved, there are many different methods of applying powered flying controls to aircraft, when considering the system as a whole.

The most important question is: shall the controls be operated only by a powered system, or should manual reversion be used in an emergency? Whereas an "all power" system can be used on any type, the use of manual reversion is limited by aircraft size and speed. This subject will not be considered here, since it has already been discussed in some detail[1].

Table I lists nine different systems for operating the controls of a hypothetical long-range aeroplane of about 100,000 lb. all-up weight. The first is suggested as the ultimate development, with an all-electric system, pilot's controls in miniature, no mass-balancing, no aerodynamic balancing and such a high degree of reliability that no duplication is required. It is not intended to forecast when, if ever, such a system will be available, but there is little doubt that it is not available today. The last system shown in Table I is a normal manual control which, although not possible to contemplate perhaps on a high-speed project, has been included for the purpose of payload comparison. Those between the first and last show some of the various stages of compromise from which the designer has to choose when considering reliability, availability of equipment, payload, requirements of a particular design, and so on.

The object of the table is to show variations in payload and value in first cost with the various schemes listed, and for that purpose take-off weight, range, cruising height and cruising speed have been assumed constant in each case.

These results are only estimates, but they do indicate tendencies resulting from the fundamental characteristics and requirements of the various systems. An interesting point, when considering civil aircraft, is that Item 3, which is probably the most advanced which could be contemplated at present without jeopardising the Certificate of Airworthiness, is worth £106,000 more in first cost than a manual control (Item 9). This indicates that an advanced system of powered controls may well pay for its development in earning capacity.

The scheme for splitting the control surfaces and operating each part with a single actuator, has considerable attractions, mainly on the score of reliability. Unfortunately, it tends to be heavy and can offer severe restriction to the basic layout of the aircraft, *i.e.* it is hardly possible when the "elevator" is in the form of an all-moving tailplane.

The advantage of manual reversion over the "all power" control is again that of reliability. As a last resort, the pilot exercises some measure of control manually. This, however, may well be embarrassing if the main power fails when the actuator is supporting a large hinge moment. Fig. 1 shows a method of overcoming this problem with continuous automatic trimming by means of a separate power-operated follow-up tab. From some points of view, this scheme is a form of duplicated control, since, if in the event of its failure the main actuator is by-passed, the powered trimmer provides a stand-by system. It is probably inadvisable, however, to fit a powered trimmer with sufficiently high rates of operation, even for emergency control purposes and the usual practice is to return the trimmer to neutral after failure of the main actuator and to carry on manually. In order to cater for a runaway failure of the power trimmer, the main actuator must be powerful enough to support the increased hinge moment with the trimmer in its most adverse position.

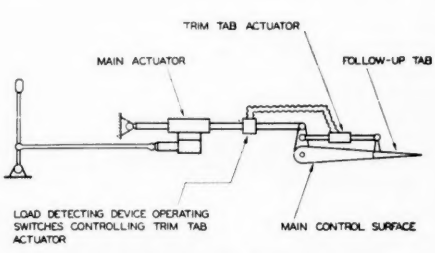


Fig. 1. Automatic follow-up trim tab

TABLE I

POWER CONTROL SYSTEMS: ANALYSIS OF WEIGHTS

Item	Type	Description	Power control system									Subsidiary effects											Total	Effect on economics	
			Signalling circuit to optimum design						Feel simulation	Main surface power units	Power supply for main surface power units	Main control surfaces				Penalty for tabs (including mass balance where required)			Structure weight change at main surfaces (torque box area, etc.)	Change in engine weight to give constant cruising speed and height	Change in fuel required for constant range			
			Pilot's controls (dual)		Control circuit		Mountings and structure					Excess structure for split surfaces, etc.	Excess structure for mass balance	Mass balance weights to AP970 requirements	Extra mechanism at control surfaces	Trim tabs	Balance tabs	Spring or servo tabs					Overall relative variation in payload	Overall loss in revenue (£/1,000) (S.B.A.C.) *
			Main	Trim, etc.	Main	Trim, etc.	Main	Trim, etc.																
1	All power. Electric signalling. No standby. Miniaturised pilot's controls	Electric actuator with remote electric signalling control. Driving screwjacks. No aero or mass balancing or feel	5	1	30	2	10	2	—	750	130	—	—	—	—	10	—	—	—	—	—	940	0	0
2	All power. Electric signalling. No standby	As (1) but with normal pilot's controls and artificial feel	80	10	30	10	10	2	70	750	130	—	—	—	—	10	—	—	—	—	—	1102	−162	31
3	All power. Electric signalling. Full duplication	As (2) but with all powered components fully duplicated	80	10	100	10	20	2	70	900	130	—	—	—	—	10	—	—	—	—	—	1332	−392	74
4	All power. Mechanical signalling. Full duplication	As (3) but with non-duplicated mechanical signalling system. Electro-hydraulic actuators	80	10	170	10	35	2	70	900	130	—	—	—	—	10	—	—	—	—	—	1417	−477	90
5	All power. Mechanical signalling. Full duplication	As (4) but with full mass balancing	80	10	170	10	35	2	70	900	130	—	25	430	—	10	—	—	—	40	100	2002	−1062	200
6	All power. Mechanical signalling. "Split" control surfaces	Each control surface split into three sections. Each section controlled by a single actuator. Mechanical signalling with artificial feel. No mass balance	80	10	170	10	35	2	70	1100	130	85	—	—	35	10	—	—	−30	60	150	1917	−977	185
7	All power with automatic follow-up trim	Main actuator operating main surface Separate actuator operating follow-up tab. Mechanical signalling with artificial feel. Aero and mass balancing	80	10	170	15	35	3	70	500	80	—	25	430	20	50	—	—	55	120	450	2113	−1173	222
8	Power boost	Single actuator with proportional feed back. Mass and aero balance	80	10	170	25	35	5	—	400	60	—	25	430	20	30	10	—	55	120	450	1925	−985	186
9	Manual control	Normal mechanical control system with spring tabs. Aero and mass balance	80	10	170	25	35	5	—	—	—	—	25	430	40	30	10	30	55	200	750	1895	−955	180

Note: All weights in lb. * S.B.A.C. standard value £27/lb. per annum for 7 years.

On almost all counts other than reliability, manual reversion is probably inferior to powered stand-by systems and on aircraft flying at very high subsonic speeds it may be impossible.

3. DETAIL CONSIDERATIONS AFFECTING CHOICE OF A POWERED CONTROL SYSTEM

3.1. Power Source and Transmission

The main engines, or perhaps in some cases auxiliary power plants, provide the power source. With an all-power system it may be necessary to provide some form of stored energy, such as electrical or hydraulic accumulators, to provide for descent and landing in the event of complete failure of the main source. On single-engined aircraft the provision of reserve energy is essential unless manual reversion is used.

Power transmission from the engines to control surface actuators can be electrical, hydraulic or even pneumatic. There are six main factors affecting the choice of a system, as shown in Table II.

Electrical power transmission can be used with any type of actuator but hydraulic and pneumatic systems are confined to actuators employing similar media.

On the score of reliability, electrical transmission is superior to a piped system, since pipe fractures due to movement of the aircraft structure, vibration, and so on, are more likely than breakages of electrical wiring. When used with hydraulic actuators, however, electrical transmission introduces the aircraft generating system, together with electric motors, into the chain of items which may go wrong. Thus, the reliability "balance" lies between electrical power generation and transmission, with electric motors, and long, large bore, constantly pressurised pipes, which may have to be heated. In all probability, the choice depends on size of aircraft, with large aircraft favouring electrical and small aircraft hydraulic transmission.

For reasons which are obvious, electrical transmission is preferable when considering points (*e*) and (*f*) of Table II, while with (*d*), aircraft size may again be the deciding factor.

When considering weight, the comparison is made between

(*i*) total length of pipes + fluid + pipe lagging + engine driven pump drives, and

(*ii*) total length of electrical cables + electric motors at acuators + motor cooling + share in weight of electrical generating system.

Figure 2 shows two hydraulic power transmission systems for the hypothetical 100,000 lb. aircraft and compares their weights with an electrical transmission used to power fully-duplicated electro-hydraulic actuators.

Regarding reliability Scheme 1 is more comparable with the electrical system than Scheme 2, since with Scheme 2 failure of two engines could put the whole system out of action. When compared with Scheme 1, electrical power transmission is probably lighter than hydraulic for this size of aircraft. On smaller aircraft, engine-driven pumps would show more advantage.

3.2. Control Surface Actuator

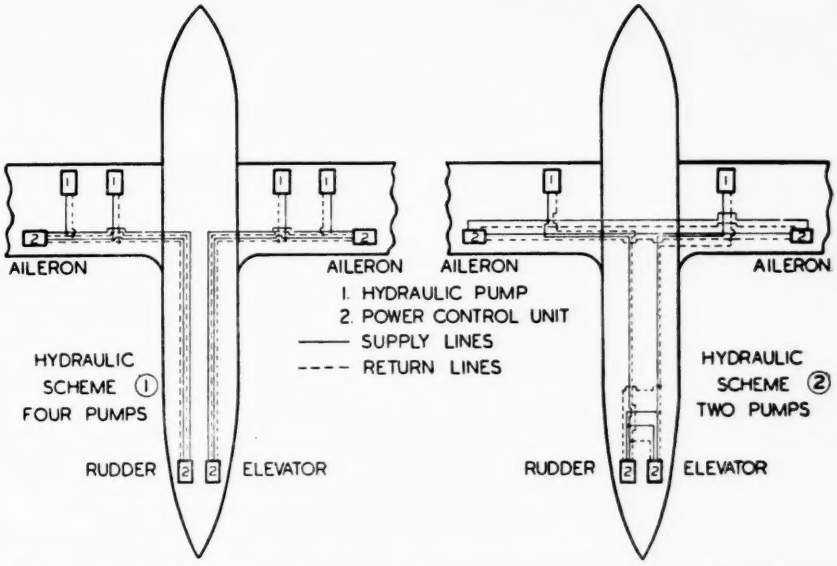
The selection of a satisfactory actuator is undoubtedly the biggest problem in the design of a powered control system. In it are centred most of the problems affecting reliability, weight and flutter prevention. Broadly speaking, actuators can be divided into three classes:—

(*i*) Those employing piston jacks.
(*ii*) Those employing screw jacks.
(*iii*) Those employing skew roller jacks.

Obviously, the piston-jack type is confined to use with hydraulic or air systems, whereas the screw and skew roller jacks can be driven by electric, hydraulic or air motors.

TABLE II
Power Transmission—Choice of System

Factor affecting choice	*Large aircraft*	*Small aircraft*
(*a*) Type of control-surface actuator	Same as for actuator or electric	Same as for actuator or electric
(*b*) Reliability	Electric	Hydraulic
(*c*) Weight	Electric	Hydraulic
(*d*) Effect of low temperature	Electric	No preference
(*e*) Vulnerability (military aircraft)	Electric	Electric
(*f*) Ease of installation and maintenance	Electric	Electric



SCHEME	ELECTRIC MOTORS	COOLING DUCTS	ELECTRIC CABLES	GENERATOR SYSTEM SHARE	HYDRAULIC PIPES	FLUID IN PIPES	PIPE CLIPPING ETC	PUMP DRIVES	HYDRAULIC PIPE LAGGING	TOTAL WEIGHT
ELECTRICAL TRANSMISSION	180 lb	40 lb	35 lb	200 lb	—	—	—	—	—	455 lb.
HYDRAULIC TRANSMISSION SCHEME (1)	—	—	—	—	295 lb	70 lb	45 lb.	80 lb.	15 lb.	505 lb.
HYDRAULIC TRANSMISSION SCHEME (2)	—	—	—	—	215 lb.	55 lb.	30 lb.	50 lb.	10 lb.	360 lb.

Fig. 2. Powered flying controls. Comparison between hydraulic and electric power transmission.

3.2.1. *Piston jacks*

The lightest and simplest form of actuator is undoubtedly that employing piston jacks. Unfortunately, even when using fluid it is doubtful if stiffness in the link between control surface and aircraft structure, when using piston jacks, is sufficiently high to permit the removal of mass-balancing.

Flutter calculations, model tests and/or flight tests may show, on a particular aircraft, that piston jacks are satisfactory in this respect. However, since taking full advantage of the absence of mass-balancing involves the basic layout of the aircraft structure, a decision must be made before there is enough information for even a preliminary flutter calculation.

This relative lack of stiffness in the piston jack is due to three causes:—

(*i*) Elasticity of the cylinder walls.

(*ii*) Elasticity of the fluid.

(*iii*) Aeration, or presence of air bubbles in the fluid.

The last, which is probably the most serious and certainly the most unpredictable, can be almost entirely eliminated by pressurising the fluid on each side of the piston, to about 500 lb./in.^{2}

Actuators using piston jacks are probably the best solution for a system on which the control surfaces are mass-balanced and, particularly, on one employing manual reversion.

3.2.2. *Screw jacks*

The simple screw jack, if properly designed, offers the best chance of eliminating mass balance, but has a number of disadvantages, as shown in Table III.

Points (*a*) and (*c*) are inherent in a screw jack and, generally speaking, one can only be improved at the expense of the other, that is to say, a light, heavily loaded screw jack will tend to have a short usable life while a robust jack with long life will be heavy.

The simple screw jack cannot be as efficient as a piston jack, but it is not necessarily essential to aim at a figure of less than 50 per cent. when used without mass-balancing. The damping effect of a jack with an efficiency up to about 65 per cent. to 75 per cent. may be sufficient to ensure flutter-free controls. This is particularly true if the screw jack is backed up by a hydraulic motor which will in itself have a high stiffness, because of the small fluid volumes involved. When considering the combination of jack and hydraulic motor, it may be found possible to use a high efficiency ball-bearing screw, an arrangement which will certainly rival the piston jack in efficiency if not in weight.

High efficiency ball screws may also be driven by electric or pneumatic motors, but in these cases, the stiffness requirement will probably demand some form of clutch or auto-lock.

"Judder" has been giving concern on a number of simple screw jack actuators recently. It is due to the difference between static and running friction and generally occurs when the jack is working with a following load. What probably happens is that the jack is fluctuating between being reversible and irreversible and, if that is so, it means that jacks with static efficiencies between, say, 25 per cent. and 50 per cent. should be avoided on power control actuators.

3.2.3. *Skew roller jacks*

The skew roller jack[3], shown in Fig. 3, consists of an inner member and an outer sleeve, with rollers in between constrained in a cage such that the axes are at a slight angle (the pitch angle) to the axis of inner and outer members. The difference between outside diameter of inner member and inside diameter of sleeve is slightly less than twice the roller diameter, thus causing a slight elastic deformation of the outer sleeve.

This scheme, which at present is in the early stages of development at Handley Page's, requires high class machining with very fine tolerances, but it offers considerable advantages, as follows:—

(*a*) Practically no wear.
(*b*) No lubrication required.
(*c*) No backlash.
(*d*) No judder.
(*e*) No adverse temperature effects.
(*f*) High efficiency between 84 per cent. and 90 per cent.

TABLE III
SCREW JACKS

Advantages	*Disadvantages*
(*a*) High stiffness—best chance of deleting mass balance	(*a*) Weight
	(*b*) Static irreversibility demands efficiency less than 50 per cent
	(*c*) Wear around mean position of nut gives increasing backlash with life
	(*d*) Judder

3.2.4. *Arrangement of actuator*

Basically, there are two ways of arranging and locating the actuator, with a number of variations of each:—

(*i*) With the power unit and screw or piston jack located at the control surface and the shortest possible hinge moment carrying mechanical inter-connection between actuator and surface.

Here the principal advantage lies in the short mechanical inter-connection which

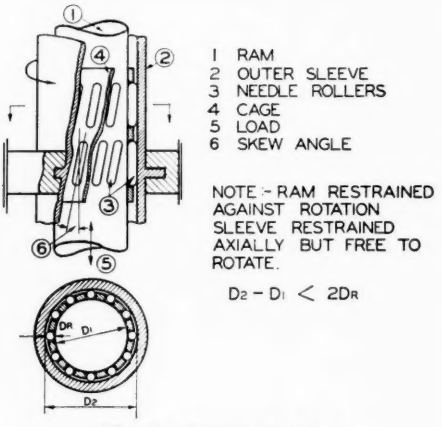


Fig. 3. Skew roller jack.

1 Electric motor
2 Hydraulic pump
3 Reservoir
4 Hydraulic motor
5 Screw jack
6 Electric cable
7 Pilot's control
8 Limiting rod
9 Follow-up lever
10 Toggle arms

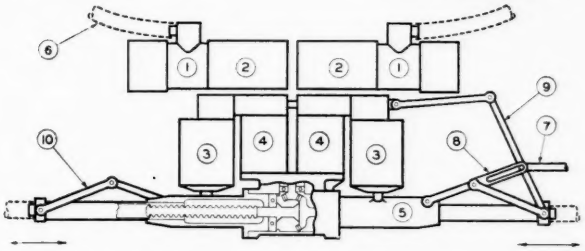


Fig. 4. Hobson double-ended power control actuator.

is relatively easy to make with a stiffness and lack of backlash, adequate to meet phase lag requirements and freedom from flutter. An example of this scheme is the Hobson unit shown in Fig. 4. Here a double-ended jack has been used with nearly equal and opposite loads in each end, thus ensuring a high actuator mounting stiffness due to the small or negligible reactions on the aircraft structure. This feature has the added advantage of making easier the problem of preventing servo instability, since there is little or no relative movement between the input rod and the actuator, when under load.

(*ii*) Alternatively, the actuator can be located remotely from the control surface with long mechanical drives carrying the full power to the surfaces, as shown in Fig. 5. When employing an all-electric actuator, this scheme has an important advantage in that high-altitude D.C. motor brush wear can be avoided by placing the motors in the pressure cabin. This advantage applies also to the remote electro-hydraulic unit which has the additional merit of enabling two or three electric motor/hydraulic pump units to provide duplication for all three control surfaces, thus reducing weight and complication. A further advantage of locating electric motors, hydraulic pumps, and so on in the pressure cabin is the possibility it offers of servicing in flight.

The main disadvantages of this scheme are the difficulties of installing long mechanical power transmission, together with its backlash and potentially low stiffness. Flutter difficulties arising from this last point can be overcome by using shaft transmission and locating irreversible screw jacks at the control surfaces.

The long mechanical power drives are obviously heavy, but this may be more than offset by the reduction in weight of actuators.

3.2.5. *Hydraulic actuators*

As already stated, pressurised hydraulic fluid may be used, either to drive a piston jack direct, or to drive a screw jack by means of a hydraulic motor.

The hydraulic pumps may be directly engine-driven or remotely driven by small electric motors.

With engine-driven pumps, hydraulic transmission of power is required between engines and actuators, the advantages or otherwise of which have already been discussed. A disadvantage of these pumps is that when the control surface rate requirements are highest, that is during approach and landing, the engine speed and therefore pump output is at its lowest.

The remote, electrically-driven pump scheme has two advantages:—

(*i*) It enables the power control actuator to be designed as a compact self-contained unit with no external pipes. Such a unit can be fully tested before assembly in the aircraft and be made easily removable for servicing under controlled conditions —an important point when considering the replenishment of hydraulic fluid.

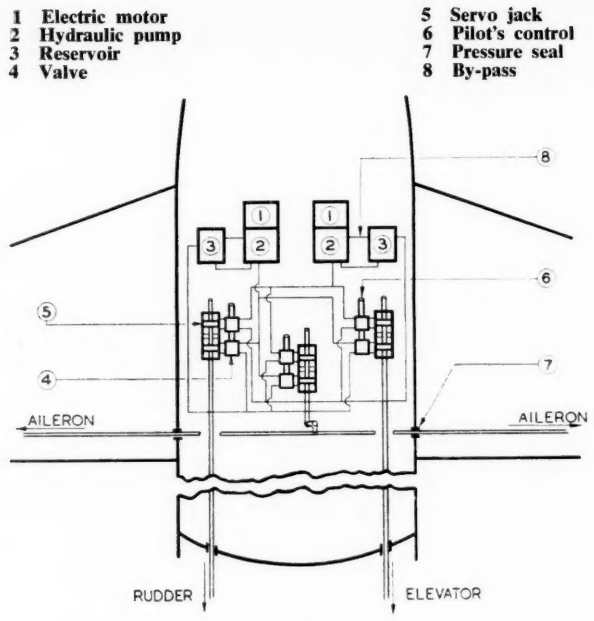


Fig. 5.

(*ii*) It makes possible the direct control of variable stroke pumps, thus dispensing with control valves. This advantage is partly counteracted if the loads required to displace the pumps are of such magnitude that servo action is required. Ideally, the pump should be balanced such that direct operation by the pilot's signalling system is possible.

On a self-contained electro-hydraulic unit, the electric motor weight may be as much as 25 per cent. of the total. It follows that more careful attention must be given to the choice of hydraulic pump for this application than when using engine-driven pumps. The characteristic requirement for a power control system is for high loads at low rates (high-speed condition) and low loads at high rates (approach and landing condition). A typical curve of end load rate is given in Fig. 6(*a*). A constant displacement pump provides a characteristic, when plotting end load against rate, as shown in Fig. 6(*b*), and will require an electric motor of power corresponding to point *A*. A variable-stroke pump could be controlled manually, such that it followed the curve shown in Fig. 6(*a*), but this necessitates the pilot's varying rate with load, an impossible situation, and one which would invariably cause him to stall an electric motor of appropriate power.

Assuming the requirement given in Fig. 6(*a*), the pump which gives the lightest electric motor weight is one with a constant work characteristic, as shown in Fig. 6(*c*). This is achieved either by using a variable stroke pump with the stroke controlled by pressure, or by a two-stage unit with gear and piston pumps[4], the pumps having an automatic device which decreases delivery with increasing pressure. With either of these pumps, valve-type control must be used.

3.2.6. *All-electric actuation*

At first sight, the use of a hydraulic pump, valve gear and hydraulic motor between the electric motor and screw jack appears a roundabout way of doing the job. Ideally, the electric motor should drive the screw jack direct, but the problem is in controlling the electric motor. A number of schemes have been proposed of which the following may be considered typical:—

(*i*) Constant speed motors—on-off control switching. This scheme can be used

with mechanical or electrical signalling and can be designed as a self-contained unit with similar provisions for duplication and fault detection, as with the electro-hydraulic scheme. Its main disadvantages are a marked tendency to instability, the constant-speed "stepped" nature of the output, high starting torque and potentially bad reliability of the high-power switch-gear and relays.

(*ii*) Constant speed, continuously running motors with magnetic clutches. Here, again, a self-contained unit can be used with either mechanical or electrical signalling and duplicated in a similar manner to the electro-hydraulic units. The magnetic clutches can be of the dry type and, after proper development, should be very reliable. The follow-up gear switches which energise the clutches have relatively low powers to handle and the driving motors can be either A.C. or D.C.

(*iii*) Variable speed motor—Ward Leonard system. This scheme is primarily suited to an electrical signalling system and, therefore, its main disadvantage, in the present state of development, is probably that of unreliability. It may also be heavy but in other respects it offers many attractive features. It probably shares with (*ii*) the prospect of becoming ultimately one of the best systems for very large aircraft.

(*iv*) Variable speed motor—thyratron control. This is also primarily a system for use with electrical signalling. The use of electronic components will obviously be considered unacceptable until they have been demonstrated as complying with the reliability requirements.

Potentially, the all-electric scheme has many attractive features, and the advantages of A.C. motors in eliminating high-altitude brush wear might be mentioned here, but the snags seem to be unreliability, excessive weight and, above all, lack of development.

3.2.7. *Pneumatic actuator*

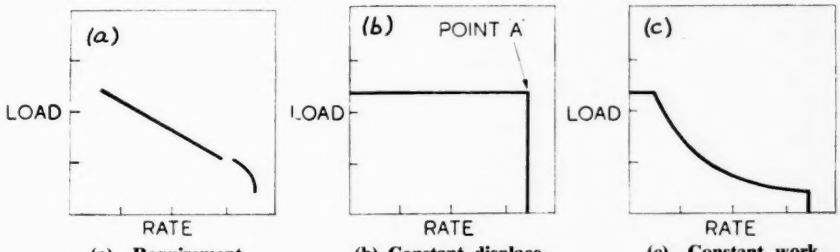
There is no fundamental reason why an air motor should not be used to drive the screw jack, although this has not yet been done on powered flying controls. Satisfactory pneumatic follow-up valve gear has been used on other applications, although careful design is required to prevent instability. Pneumatic motors have a reputation for light weight and successful high pressure compressors have been developed recently. One obvious difficulty would be the reduction of damping in an air motor compared with a hydraulic motor when used with a high efficiency screw.

It would be interesting to know the views of pneumatic engineers on this application of air.

3.2.8. *Duplication*

In spite of its simplicity and light weight, many years of development will be required before a single actuator can be relied upon as the sole means of operating main flying control surfaces.

It follows that stand-by facilities must be provided on all except, perhaps, some specialised military application. Provision of stand-by by manual reversion with and without automatic trimming, and split control surfaces, have already been mentioned.



(a) Requirement

(b) Constant displacement or variable displacement with pilot-control.

(c) Constant work pump.

Fig. 6.

The other widely accepted method is by duplication of those parts of the system which cannot be argued to have the same degree of reliability as a normal manual control system. There is little doubt that on this basis, items such as electric motors, hydraulic pumps and motors, must be duplicated. Valves and hydraulic jacks must be duplicated, in order to make independent the two hydraulic systems. If it is assumed that neither of these items will ever seize, then a relatively simple unit is possible in which the faulty half can be motored freely by the sound half. If the jack is assumed to seize, then a mechanical disconnection must be arranged on the output side. Duplication is probably unnecessary in the case of the simple screw jack and here the faulty half unit can be de-clutched or, in the case of a hydraulic drive, the fluid supply can be cut off and the hydraulic motor allowed to be motored freely by the sound half.

There are a number of schemes, mechanical, electrical or hydraulic, for detecting and disengaging a faulty half unit, and generally speaking, they all work on the error-operated principle. Lack of correct response causes the pilot's load to be increased in the signalling system input to the faulty unit. This increase in load operates a mechanical break-link[5], spring-loaded electrical contacts[6], or a hydraulic device which, in turn, performs a further function such as switching off an electric motor, de-clutching a drive, open porting a hydraulic circuit or changing over a mechanical output. A typical device of this sort using a shear pin as the mechanical break-link, is shown in Fig. 7.

A point to remember is that since the device is "triggered off" by the actuator input load exceeding a pre-determined amount, any snatching of the controls, particularly if accompanied by excessive inertia on the actuator side of the device, may inadvertently cut out *both* sides of a duplicated unit. For this reason it is desirable to inter-connect the devices such that they cannot operate both together.

The duplicated actuator can be arranged either:—

(*i*) By having a second actuator, normally idle or "off load," which is arranged to take over when the primary actuator fails, either automatically or as a result of some positive action by the pilot, or

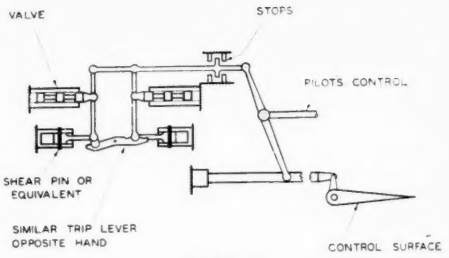


Fig. 7.

(*ii*) Two actuators, which normally share the load, with provision for automatic detection and disengaging of either, in the event of its failure.

It is considered that scheme (*ii*) is probably the best, its only disadvantage being that in the event of failure, the remaining actuator operates the controls at half load or half rate. This is usually acceptable as an emergency condition, although in some cases the "one actuator failed" case may dictate design power requirements for the unit. Scheme (*ii*), however, does demand an absolutely reliable detection and disengaging device, designed such that failure of the device itself does not precipitate a general failure.

The disadvantages of scheme (*i*) are that it is invariably heavier, since each actuator is capable of full power; also even with automatic switch-over, some time delay is inevitable and with a runaway control could lead to catastrophe. It is suggested that 1/20 second is probably the maximum time that can be allowed for change-over on modern high-speed aircraft.

3.3. Pilot's Controls

If manual reversion is used for stand-by, then obviously, the pilot's controls must be of the conventional type and size and designed to the normal strength standards.

This also applies with an all-power system if mechanical signalling is used, since the pilot can probably apply control at a higher rate than that for which the actuator is designed, thus subjecting the signalling system to the maximum pilot's effort, that is, he can "beat" the actuator. Rate restriction at the pilot's controls would cure this difficulty but, at the same time, would introduce a further potential source of failure.

"Miniaturised" controls, with the consequent increase in pilot's comfort, improvement of flight deck layout and reduction in weight, becomes an attractive possibility with an electrical signalling system. This is already done in the pilot-monitored auto-pilot system, and there seems no reason why, ultimately, it should not replace normal controls and become the standard method of piloting aircraft fitted with all-power controls.

3.4. Signalling System

Having swallowed a fully-duplicated all-power control actuator, the average designer gets a kind of mental indigestion and tends to cling to the good old-fashioned mechanical control circuit between pilot and actuator. In point of fact, that is about the only thing he can do, since there seems to be no electrical signalling system available at present, with the required degree of reliability. There are some most excellent methods in existence, working on the "Magslip," "Potentiometer" and similar principles, but no one would claim that any *single* electrical system has the same degree of reliability as a robust mechanical control run. The best way of ensuring adequate reliability with electrical signalling is by duplication. Here the difficulty is to design completely independent circuits with some method of detecting and automatically disconnecting a faulty circuit. Another method is to have two systems with a means of indicating when one fails, such that the pilot can switch it out. The obvious snag with this scheme is the time delay between failure and corrective action, which might be serious with a runaway type of failure.

When using manual reversion, a mechanical signalling system of conventional strength is essential. With all-power controls, provided that the feel-simulators and auto-pilot servos can be accommodated adjacent to the pilot's controls, there is a temptation to use a light mechanical signalling system, since the valve or other input loads at the actuator are usually not more than one or two pounds. Unfortunately, as already mentioned, the pilot can usually "beat" the actuator and, therefore, the system must be up to normal strength standards, unless the additional complication of a rate restrictor is considered worthwhile.

The use of a duplicated hydraulic actuator, with error-operated fault-detection devices requiring an input load which may be as high as 10 to 20 lb., favours a mechanical signalling system.

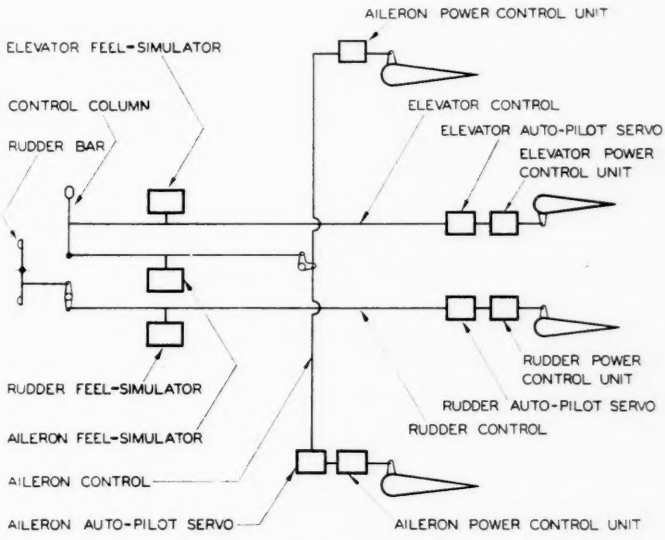


Fig. 8. Location of auto-pilot servos.

3.5. AUTOMATIC PILOT

Lag in response in a powered control system is a most important consideration and this is particularly true when using it with an automatic pilot.

The well trained human pilot with his anticipatory instincts can deal with a certain amount of lag, particularly when he knows the aircraft. Furthermore, he usually neglects small periodic oscillations which are smoothed out by the natural damping of the aircraft. In automatic flight, however, the gyros cannot differentiate between a small oscillation and, say, the onset of a divergent disturbance; thus a correcting signal will always be sent to the control surfaces. The effects of this signal may increase the damping or make the oscillation divergent and produce instability. The important criterion is the relationship between the time lag, (between a disturbance and the onset of the aircraft righting moment) and the natural periodic time of the aircraft. A small lag is probably acceptable but, in any case, provided that it is linear with amplitude and not really excessive, the modern auto-pilot can provide correction by means of phase advance. Unfortunately, the auto-pilot cannot deal with a lag which is irregular and varying with amplitude. Backlash and lost motion in any part of the system between auto-pilot servo and control surface results in a most irregular lag and one which varies considerably with amplitude. In fact, with excessive lost motion and very small amplitude inputs, the output can disappear altogether.

This difficulty is not new; it applies to all manually-operated controls, but it is aggravated by the power control actuator and its effects are worse on modern high-speed aircraft, having short natural periodic times and requiring small control surface angles when in automatic flight.

Power control actuators requiring high input loads bring in elastic distortion of the signalling system as additional lost motion, since the system will deflect until the input load has been reached before there is any response.

Owing to the difficulty of assessing accurately the overall lost motion and determining exactly what it means in terms of phase lag, it is impossible to be sure that the system is stable in the design and rig-testing stages; that can only be checked by flight trials.

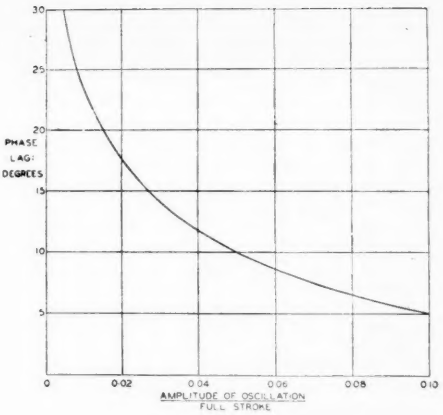


Fig. 9. Phase lag of actuator.

What can be done, however, is to ensure that the most adverse factor, *i.e.* lost motion between auto-pilot servo and control surface, is an absolute minimum.

This can be done best by providing the shortest possible length of control run from the auto-pilot servo to the power control actuator input and a short, stiff inter-connection between actuator output and control surface. Such an arrangement is shown on Fig. 8 and is quite practicable for elevator and rudder circuits. On the aileron circuit, however, the auto-pilot servo must be situated close to one aileron actuator and backlash in the aileron inter-connection signalling circuit accepted as inevitable.

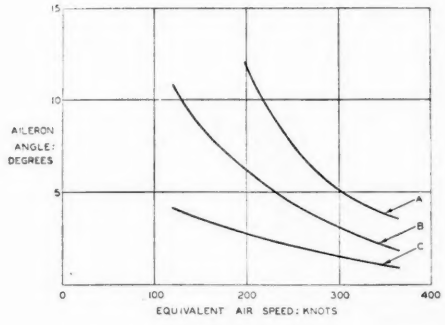


Fig. 10.

Curve A Structural limitation
Curve B Maximum auto-pilot angle
Curve C Minimum auto-pilot angle

This location of auto-pilot servos provides an additional argument to those already advanced for not fitting a light mechanical signalling system, since with human pilot and auto-pilot at opposite ends of the aeroplane, as it were, the control run in between, irrespective of the location of the feel-simulator, must be up to the normal manual control strength standards.

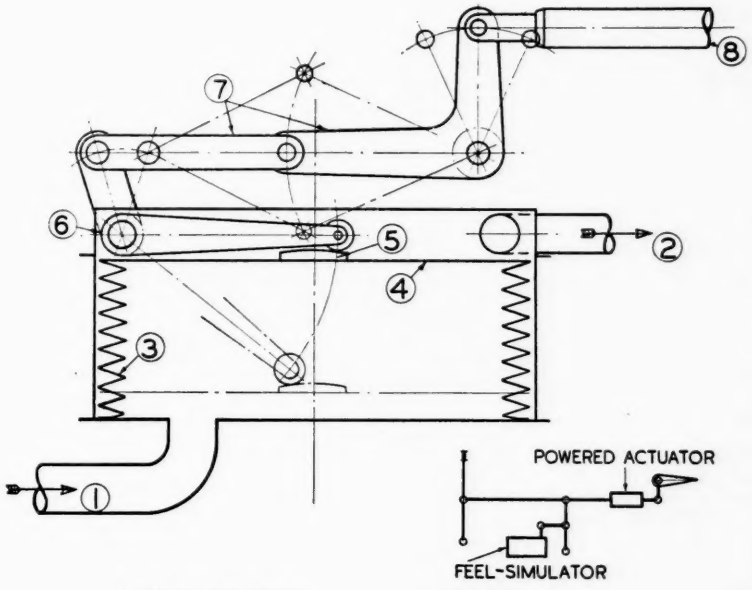
All mechanical follow-up systems work on the "error-operated" principle, that is, a deliberate de-phasing between input and output is used to "turn on" or "turn off" the power. With most systems, the hydraulic valve with "overlap" being a typical case, the linear magnitude of this error is independent of amplitude, thus making an additional contribution to lost motion in the system as a whole.

Figure 9 shows the effect of this lost motion as phase lag plotted against percentage of full stroke for a typical valve-type hydraulic actuator.

There are various methods of reducing the magnitude of the error, such as, with the hydraulic actuator, the "floating valve" or valve with negative overlap. Unfortunately, actuator instability or hunting is likely to result if the error is made too small.

Here again, the ultimate solution may well be the all-electric actuator and, in particular, the electric signalling system, working on rates of control application instead of position error.

The problem of installing an automatic pilot which will have sufficient power to control the aeroplane in automatic flight but, at the same time, not enough to break the aeroplane in the event of a "runaway" type of failure, usually presents difficulties on a manually-controlled aeroplane. With power controls, and especially with a duplicated actuator having an error-operated fault-detection system, the problem becomes much more complex. The normal input signal load is not likely to be more than one or two pounds per valve but, to prevent inadvertent operation, the fault detection device requires a load of some 10 times that amount.



1 Total head intake
2 Static vent
3 Flexible bellows
4 Piston
5 Cam
6 Seal
7 Crank linkage
8 Connection to pilot's control

Fig. 11. Direct type feel-simulator.

It follows that the auto-pilot servo power must be adequate to control the aeroplane, when resisted by the feel-simulator, the most adverse circuit friction and normal valve loads; at the same time, it must be capable of operating a fault-detection device. Its maximum power, however, must be such that, in the event of a runaway, it cannot break the aeroplane if these various contributions to "feel" are at their lowest value.

A typical case is given in Fig. 10 showing, with aileron angle plotted against equivalent air speed (E.A.S.):—

Curve A—Conditions of angle and speed which give ultimate loads on the aircraft structure.

Curve B—The maximum angle which can be applied by the auto-pilot servo with circuit friction, valve loads, and so on, all at their lowest.

Curve C—The maximum angle which can be applied by the auto-pilot servo with friction loads, and so on, at their highest, and one detection device operating.

In this particular case, a runaway auto-pilot cannot break the aeroplane, but it is clear that these considerations demand low and consistent actuator input and friction loads, and reasonably low loads for operating the fault-detection device.

4. PILOT'S FEEL

If manual reversion is being used, there is little doubt that the simplest method of providing feel is to feed back a proportion of the control surface hinge moment. This system of proportional feed-back has been widely used and is well known, but its application is obviously confined to power controls of the reversible type where mass-balancing is essential and probably to aircraft cruising at relatively low subsonic speeds.

With an all-power irreversible type of control, some form of artificial feel is necessary. There has been much argument about the relative merits of feel proportional to V, V^2 or V^3, while some claim that a simple spring feel is adequate. There seems little doubt that on aircraft fitted with auto-pilots, feel must vary with some function of speed, unless the danger of a runaway auto-pilot breaking the aeroplane is accepted, or dealt with in some other way.

At one time, if given the choice, the average designer would have said that feel should vary with V^2. On modern aircraft with large speed ranges, however, even without power controls, much effort is spent on beating the speed square law, *i.e.* using spring tabs, aerodynamic servos, and so on. It is suggested that no general requirement can be laid down and each aircraft type must be considered on the basis of its operational functions. For example, a fighter must have light aileron controls at high E.A.S., while a high altitude bomber, in order to provide a steady bombing platform should have a heavy rudder at relatively low E.A.S. The best plan seems to be to write down the desirable pilot's loads for various operating conditions for a given type, and then to try to design the feel-simulator to meet them.

Broadly speaking, artificial feel-simulators can be divided into two types:—

(*i*) Direct force provided by dynamic pressure[7], and

(*ii*) Force provided by some auxiliary means controlled by dynamic pressure[8].

An example of the first scheme is shown in Fig. 11. Here, stick displacements are resisted by dynamic pressure and the characteristics modified by varying the area of the bellows and the cam shape. This scheme is undoubtedly the simplest and probably the best, provided that there is sufficient space to accommodate the bellows, which may be large if the desired pilot's loads are high.

Scheme (*ii*), an example of which is shown in Fig. 12, is a spring feel arrangement, with the relationship between pilot's control displacement and spring displacement varied by an actuator, which is controlled by dynamic pressure. With this scheme, dynamic pressure balances the diaphragm against a spring or springs, chosen to give the desired feel characteristics.

Variations in forward speed result in movements of the diaphragm, which controls power to the actuator by means of electrical contacts and a follow-up gear. The advantage is that, since dynamic pressure is used only to make and break contacts, the bellows can be small. Its disadvantage is the use of auxiliary power with the accompanying risk of failure.

What might be regarded as a compromise between Schemes (*i*) and (*ii*) is to use dynamic

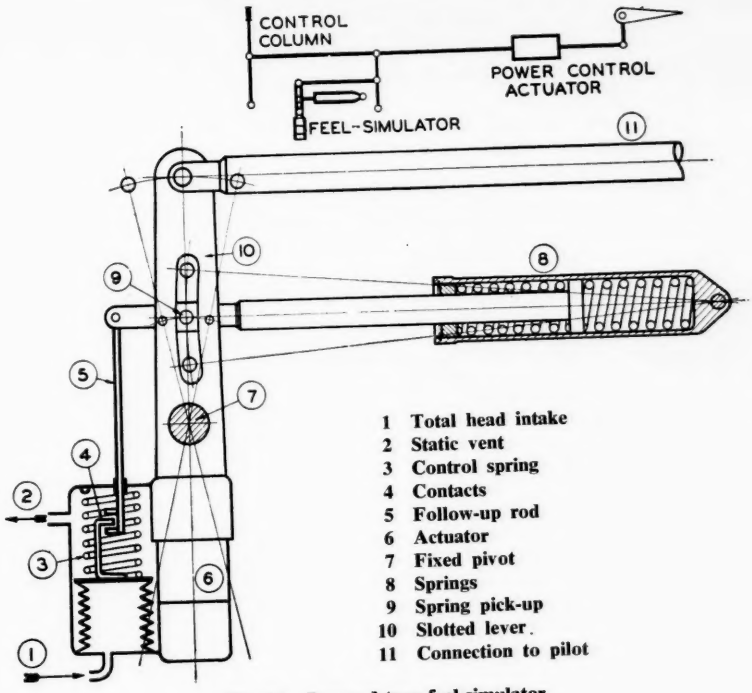


Fig. 12. Powered type feel-simulator.

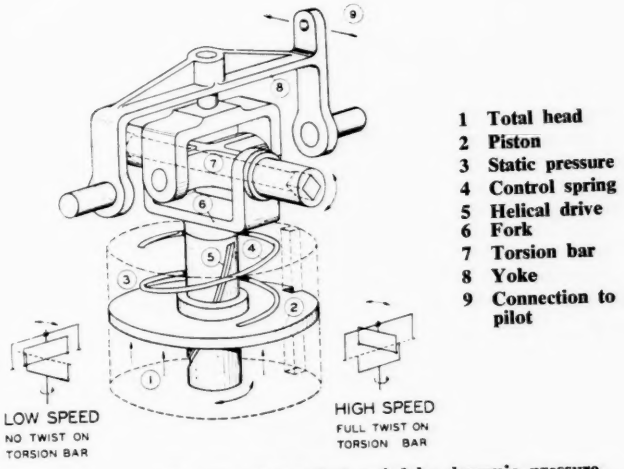


Fig. 13. Spring feel varied by dynamic pressure.

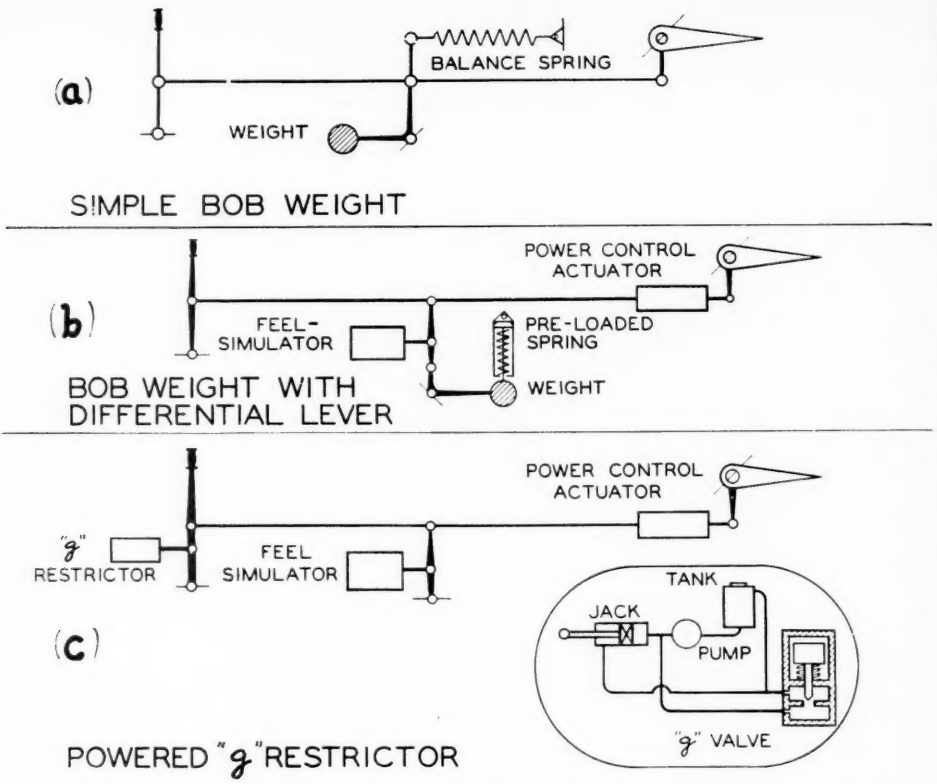


Fig. 14. "g" restrictors.

pressure directly, through an irreversible mechanism, to modify the gear ratio between controls and spring[9]. This scheme, which is shown in Fig. 13, has the advantage of a relatively small space requirement. Its disadvantage is that if the controls are held in an untrimmed position, during a speed build-up, there is insufficient power to "wind up" the torsion bar and to increase the pilot's loads to a value appropriate to the higher speed. However, the difference is likely to be small and probably acceptable.

If an electrical signalling system is used, the problem of feel is almost entirely confined to the feel-simulator. With mechanical signalling, actuator input loads (particularly if large) and friction, have an important influence on feel. There is little doubt that on mechanically-signalled all-power controls, low friction values are of even greater importance than on manually-operated controls. It is not possible to generalise when specifying actual figures, but even on large aeroplanes, and particularly if an automatic pilot is used, it is doubtful if a value greater than 5 lb. at the pilot's controls can be tolerated. Even with friction of this order, it may be necessary to provide a centralising spring in addition to the feel-simulator.

Hydraulic actuator valve loads can have queer characteristics and can be troublesome. The maximum load is produced by a combination of "stiction," friction and dynamic effects. The magnitude will depend, to some extent, on the rate of control application and under certain conditions might even be negative. These variations will result in a lumpy feel unless the actual magnitude of valve load is kept very low.

"g" restriction or "g" feel is a subject which always arises when discussing artificial feel. Strictly speaking, of course, if a "q" feel, or feel varying with forward speed, is provided, there is no more need to include some function of g in the pilot's stick loads on a power-controlled aeroplane than on one with manual controls. However, with high indicated air speeds and, with large modern aircraft, relatively low ultimate factors, a means of introducing g into the artificial feel is probably desirable if not essential.

Figure 14 shows three methods of increasing stick force with increasing g:—

(*a*) By means of a simple "bob" weight in the control run.

(*b*) By combining the "bob" weight with a feel-simulator through a differential lever[10].

(*c*) By means of a powered "g" restrictor[11].

The main disadvantage of Scheme (*a*) is that the stick force is a combination of force due to the bob weight and aerodynamic force on the elevator, the bob weight making itself felt at all accelerations over 1g. Thus, at a given high value of g, stick force will vary with aircraft weight and c.g. position.

With Scheme (*b*), the spring which balances the bob weight can be pre-loaded to any desired value of g and until this value is reached, the normal feel is unaffected by g. Above this pre-set value, "g" feel replaces the normal feel, which cannot then be felt on the stick. Thus, above this pre-set value of g, stick force is quite independent of aircraft loading and c.g. position.

In some ways, Scheme (*c*) is a combination of (*a*) and (*b*). Here again, the spring can be set such that "g" stick forces come in at any desired value. However, since its effect on the stick is additional to normal feel, stick forces will vary with weight and c.g. position. The other disadvantage of the powered "g" restrictor is the fact that it does use auxiliary power, which inevitably increases its fallibility.

5. AVAILABILITY OF EQUIPMENT

Earlier in this paper it was stated that the designer has a wide field of choice when considering types of system for use in a power-controlled aeroplane. In theory, this is true and a long and very interesting time can be spent in considering the system as a whole, and in finding the optimum solutions to the various parts of the problem. The result will probably be almost infallible, have ample power, and weigh about half as much as the average manual control. It looks satisfactory and everyone is pleased, until someone starts looking round for the equipment. It then transpires that most of the optimum solutions involve "hardware" which is not even in the development stages.

To the aircraft designer it always seems strange that the time taken to develop, say, a hydraulic pump, is practically as long as that taken for an aircraft. When he adds to this the fact that he cannot define his precise power-control requirements until at least the mid-stages of the aircraft design, he is forced to conclude that he must accept equipment which, if not already in existence, is at least in an advanced stage of development.

It seems that at least one of the reasons why the designer refuses to be too venturesome on his new power-controlled project is that he fears that the equipment will not be available.

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*Some Aspects of Aircraft Design and Manufacture for Limited Production**

by

W. S. HOLLYHOCK, A.F.R.Ae.S.

1. INTRODUCTION

The emphasis in this paper is on design because the author is engaged on design work and, therefore, is more competent to deal with design than with manufacture. In any discourse on design, however, consideration must be given to the available capacity for manufacture, as this has a considerable bearing on the subject.

When two aspects of a subject are so closely related, it is difficult to avoid digression, but every effort has been made to present the various—and often conflicting—desiderata clearly and in true perspective. The aim has been to draw true comparisons between the merits of the different materials and methods of treatment and joining for typical cases of design, bearing in mind the design requirements, size of order and capacity of the shops.

2. GENERAL

It is a fundamental drawback of aircraft design that the criteria are nearly all antagonistic. This feature is inherent, to a greater or less extent with all engineering design, but the conflict is much more acute with aircraft than with other branches of the engineering industry. There is little difference in character between the basic factors governing the design of large aircraft and small aircraft, or between civil and military types, but the order of precedence may vary considerably. It will be affected by a number of factors, including to some extent it must be admitted, the particular preference of the individual designer concerned.

The main criteria are well known and may be summarised as:—

Strength,
Weight,
Manufacturability and
Cost.

"Manufacturability"—an expressive, if somewhat inelegant term—covers such factors as "machineability," fabrication time, raw material availability, delivery expectations, and so forth. The other three are obviously more direct and well defined and, therefore, need no amplification for the purpose of this paper.

So far as precedence is concerned, the order indicated is correct for single-engined, military, operational aircraft, but would be incorrect for, say, a large air liner or a freight carrier. The extremely limited scale of production which usually obtains, however, presents the same kind of problem, to a greater or less extent, whatever the size and type of machine. During the 1939-45 War, when fighters and bombers were produced in comparatively large numbers, the choice of methods became easier although to some extent this was offset by limitation of material supplies and the fact that orders were "farmed out" to 'shadow' and 'daughter' factories. The majority of contracts, however, are for quantities which do not warrant the tooling and mass production methods which alone can give really high production rates at low cost. The probabilities of follow-up orders and spares requirements have a bearing on tooling scales but, unfortunately, the rosiest prospects are apt to change almost overnight and it is extremely risky to anticipate too optimistically in this direction. On the other hand, the tooling and production layout for military aircraft should be sufficiently flexible to permit rapid expansion on the outbreak of hostilities, without prejudicing the speed of building of the first few aircraft of the type. This is important because all the Service experience for the elimination of faults will be gained on these early machines.

Another factor which must be borne in mind where military aircraft are concerned, is that supplies of specialised peacetime products and materials are likely to dry up when a war begins and, therefore, design should be such that substitute materials can

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be introduced without serious loss of efficiency.

Thus it will be seen that, whatever type of aircraft is concerned, the operative word in tooling and, therefore in most detail design, is compromise.

The actual design features which it is proposed to consider in this paper are the methods of preparation and fabrication of metallic parts of the primary and secondary structure.

The basic categories of metallic materials, apart from tubes, are:—

A. Machinable solids.
B. Sheet and strip.

Tubular construction will not be considered, because welded steel tube frame construction is a specialised technique and not incidental, and the treatment of incidental tubular work is generally so prescribed as to allow the designer little choice.

The raw materials of Category A are:—

(*i*) Bar.
(*ii*) Forgings, including drop stampings and upset forgings.
(*iii*) Castings, including sand, gravity die, pressure die, "precision" and centrifugal.
(*iv*) Extrusions.

and the methods of joining:—

(*a*) Bolting.
(*b*) Riveting.
(*c*) Welding.

The methods of joining the raw materials —sheet and strip—of Category B are:—

(*a*) Bolting.
(*b*) Riveting.
(*c*) Welding.
(*d*) Brazing.
(*e*) Sweating and silver soldering.

Riveting may be sub-divided into:—

(*i*) Solid riveting.
(*ii*) Tubular riveting.
(*iii*) Blind riveting.
(*iv*) Rivet welding.
(*v*) Spot welding.

(*iv*) and (*v*), although not strictly riveting processes, are included here because they produce a type of joint more nearly akin to riveting than to welding.

Welding is divisible into:—

(*i*) Gas welding with steel rod.
(*ii*) Electric seam- and spot-welding.
(*iii*) Bronze welding.
(*iv*) Copper welding.

(*iii*) and (*iv*) are not true welding processes, since fusion does not take place, but they produce a joint which is similar to welding for all practical purposes.

Thus it is apparent that the designer has a wide choice of materials and processes for fabrication, although a number of factors operate to limit the choice in specific cases. It is these factors which govern to a great extent the type of design which will be chosen eventually for a particular job, although there will always be considerable scope for the exercise of the designer's own preferences. The most important of the factors is probably the magnitude—or otherwise—of the order, which will dictate the extent of tooling that can be undertaken, and the capacity available in the various manipulating departments.

3. CHOICE OF MATERIAL

Consider a part which must be rigid, but is not very highly stressed and which must have good mating surfaces. A light alloy pressure die casting is indicated, but this is not economically possible unless the quantity required is of the order of 5,000. If the number of aircraft to be built is, say, 500 and there are two castings per machine, then, with possibly 30 per cent. spares and a 10 per cent. contingency allowance, the total number of castings required is 1,400. This is not usually sufficient to warrant pressure die casting. In most cases, however, gravity die castings would be justified for such a quantity and, although more subsequent work on the parts would be necessary than with pressure castings, there would be a decided economy over sand casting. Furthermore,

TABLE I

COMPARISON OF SAND AND DIE CASTINGS

Number of parts required	1,000	
Cost of sand castings ...	5/- each	
Cost of patterns		
(2 off at £5)	£10 0 0	
Total cost of 1,000 sand castings		£260 0 0
Cost of gravity die castings	3/- each	
Cost of dies	£50 0 0	
*Cost of 50 (pre-production) sand castings...	£12 10 0	
Cost of 1 pattern	5 0 0	
Cost of 950 die castings	142 10 0	
Cost of dies	50 0 0	
		£210 0 0
Net saving on die castings		£50 0 0

**N.B.*—It is frequently desirable to make a small number of sand castings to avoid delaying initial production while dies are being manufactured.

the parts would be of better finish, stronger and less liable to porosity defects.

The magnitude of the financial economy is exemplified by the case shown in Table I.

Furthermore, should there be any follow-up orders, the cost would be only 3/- each and deliveries would be much better than with sand castings, since the tools would be available immediately. It is assumed in this particular example that one set of dies would last well over 2,000 castings, whereas the wood patterns for sand castings would probably need replacement after every 500 off.

Consider next a common type of plate fitting. If the number required is 100 or 200, routing is indicated but, for quantities of more than 500, "blank and pierce" tools are usually justified. If, however, the press shop is already loaded, it may be more expedient to rout even comparatively large quantities rather than wait for capacity, or sub-contract. It should be noted also that profiling around bolt holes, etc., for the purpose of saving weight, increases considerably the cost of blanking tools, but makes comparatively little difference to the cost of routing templates. Therefore, routing is a method not to be lightly dismissed.

The question of forging as against machining from bar, is less difficult to resolve, because forgings are much more economical for quantities of more than five, or ten or twenty, according to the complexity of the machining operations required. In fact, it is seldom profitable to machine more than three off any item which is at all suitable for forging.

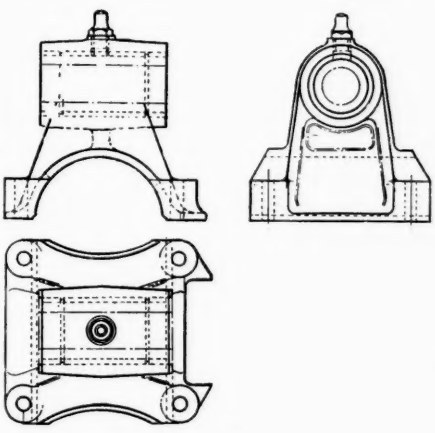


Fig. 1.

TABLE II

COMPARISON OF FABRICATED CONSTRUCTION AND CASTING

SMALL BRACKET, APPROXIMATE VOLUME 10 CU. IN.

Construction	*Costs*			
	Tools and dies	*Material (each)*	*Labour and overheads*	*Total (each)*
M.S. plate welded	£205	7d.	10/6	£1 11 7
L.A. casting	£145	2/1½	3/1	19 8½
Total saving on 200 off, as L.A. casting = £118 15 0				

A more common problem is the choice between forging and platework. Here the question usually resolves itself into whether the extra weight of the forging is justified by:

(*a*) its rigidity, or

(*b*) the reduction in cost for quantity.

The latter is governed by considerations of complexity of machining in the case of the forging and of assembly jigging for the built up plate fitting.

The examples of relative cost of fabricated, as against cast or forged, parts shown in Table II (*see also* Fig. 1) and Table III (*see also* Fig. 2), are illuminating.

Total cost of each part is on the basis of 200 off.

Had the quantity, in the case of the cantilever beam, been 2,000 off, the position would have been different and the loss on the forging version would have been changed to a saving of £3,770 16s. 8d., because the tool costs would have been spread more effectively.

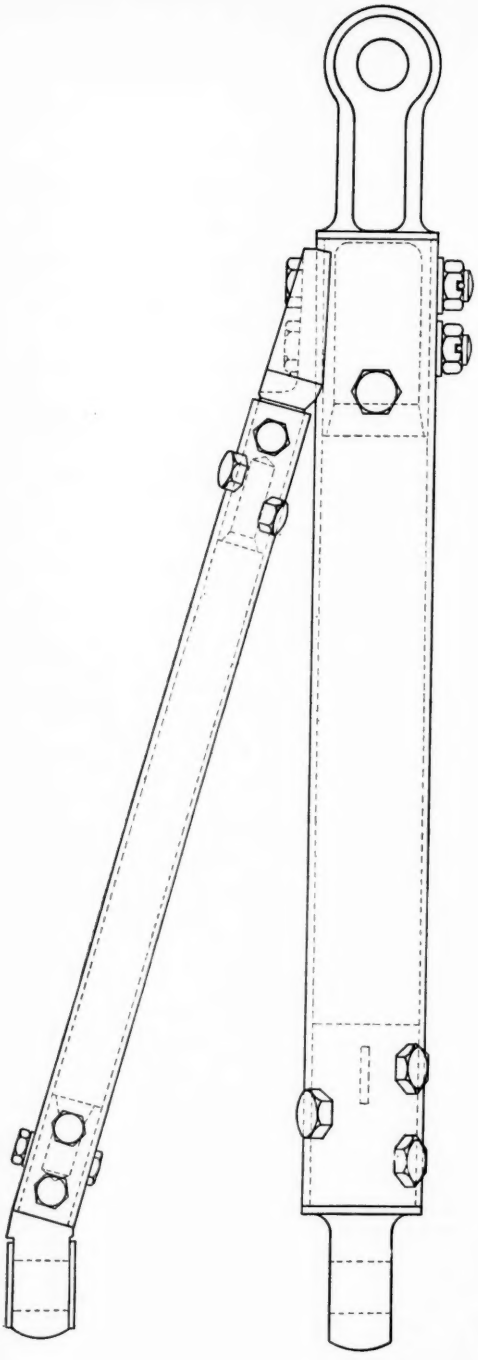
This example shows clearly the effect of size of order on design.

Table IV and Fig. 3 show a further example of the relative cost of forging, as against fabricated plate.

4. METHODS OF JOINING

When alternative methods of joining are considered the issues are still more confused and the designer's own preferences can claim more attention, although quantities have a decided bearing on the answer.

Bolting and riveting are straightforward conditions and their merits are almost entirely unaffected by the size of the order, but many fittings which may be suitable for



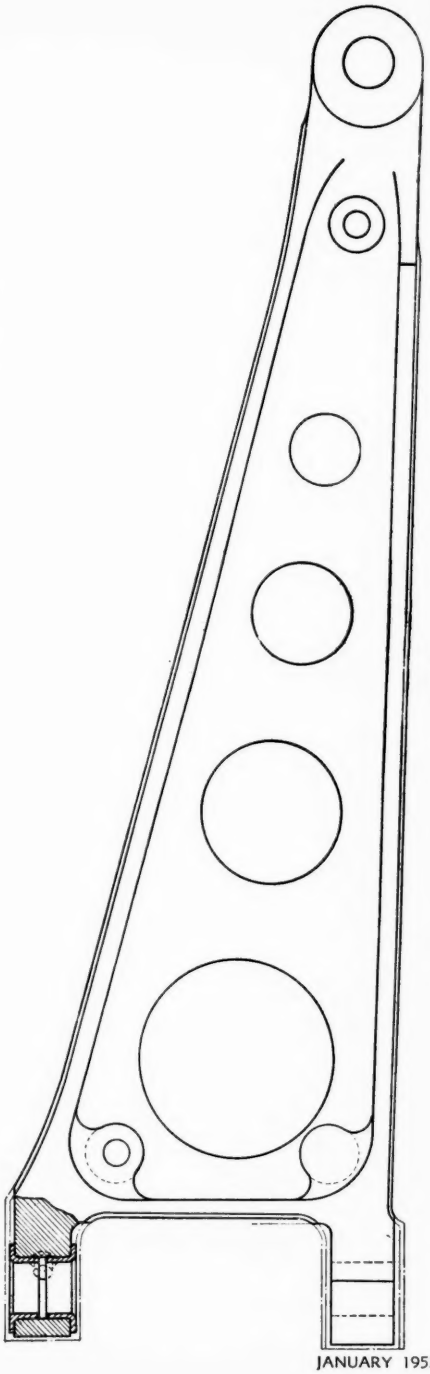


Fig. 2.

TABLE III

COMPARISON OF FABRICATED CONSTRUCTION AND FORGING

CANTILEVER BEAM, APPROXIMATELY 18" × 6" × 1½"

Construction	*Steel tube and machined fittings*	*Steel forging*
Costs—		
Tools and dies	£125	£599 10 0
Material (each)	14/1½	18/10
Labour and overheads	£3 16 4	£1 9 2
Total (each)	£5 2 11½	£5 7 11½
Weight (each)	6 lb. 11 oz.	7 lb. 13 oz.

Total loss on 200 off, as forging = £50 0 0

It is to be noted that there is a slight weight penalty with the forging, but it caters for a load which the fabricated part could not take.

either riveting or welding, so far as their design is concerned, can only be joined expeditiously by riveting, since welding would necessitate far more elaborate jigs than are warranted for orders of, say, one hundred off. On the other hand, some simple welded parts, requiring little jigging, work out cheaper and quicker than would be the case with riveting—for both large and small quantities—because rivet holes require drilling jigs, small holes not being suitable for piercing, whatever the quantity concerned.

The choice of welding as a method of joining is perhaps more a question of policy, or prejudice, than expediency. Some designers dislike the process and will only consider it as a means to an end. Other firms have developed it to a high degree and consequently will tend to use it to the exclusion of other methods. Since they will have built up an organisation and a team of operators specialising in the technique and will also have acquired a mass of information on the subject, such companies are justified in using it in complex cases, where others would be well advised to resort to different methods.

Bronze welding is a useful type of joining for mild steel parts in certain cases. Although very similar, in practice, to ordinary gas welding—which for purposes of differentiation may be termed 'steel' welding—it is essentially different in structure, in so far as there is no fusion of the metal. In this respect it is more akin to soldering but with the decided advantage that it gives a much stronger bond. Provided that care is exercised in the operation, it is comparatively easy to obtain satisfactory results and there is less risk of damaging the parent metal by over-heating. In certain cases, it is expedient to use both steel and bronze welding on a fitting, but care in design is necessary to ensure that the former operation can be carried out first and the practice is not to be generally recommended.

Silver soldering is a method which is used, on occasion, for joining such items as tungum pipes and brass flanges. It is cheap, satisfactory and reasonably simple, but the applications are limited.

Soft soldering requires less skill than silver soldering, but this has little bearing on the choice, because soft soldering is an inferior method of joining parts. Sweating has limited applications, although where it is suitable there is no real alternative.

The operator's skill is a factor which must always be considered and, in some instances, it will determine ultimately the method of joining. For example, a particular mild steel fitting might be either brazed, bronze welded or steel welded, so far as design and functional suitability are concerned. As steel welding requires a higher standard of skill than bronze welding to make a good weld and keep the temperature low, in order to minimise distortion, bronze welding will be preferred. Brazing also may be less desirable, although this would be on account of cost, rather than the skill of operator.

5. FABRICATION CRITERIA

One of the difficulties confronting production departments when orders are comparatively small, is the economic arrangement of skin and other rivet hole drilling. The full benefits of what is termed "Meccano" work are only possible with very elaborate tooling and several factors have a bearing on this matter. If the order is a small one, but there is a moral certainty of follow-up contracts, it is wise to tool more expensively than would be justified by the initial order. Subsequent aircraft can then be built more cheaply and more quickly. Also, if 'daughter' firms are to build the same type, their requirements should be taken into account. In this connection the sub-contracting of blanking and drilling jobs from the daughter firm to the parent may be well worth while in order to obtain maximum use of tools. These considerations will often have a bearing on design to the extent of

Fig. 2.

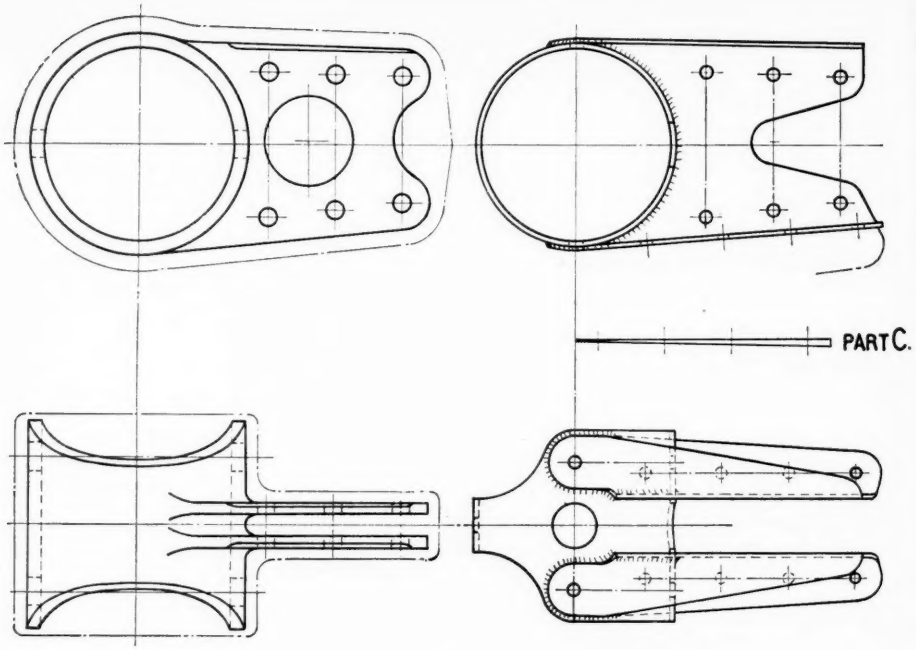


Fig. 3.

deciding whether parts shall be fully and independently detailed, for Meccano tooling, or arranged for the drilling of one part from another on assembly. Where large skin details are concerned, if quantities are not great, it will usually suffice to quote the drilling on only the skin (or the ribs, etc., according to shops preference), the mating parts being drilled off on assembly. The initial holes should be undersize, of course.

In difficult cases of contour matching and other similar circumstances, the production departments will generally prefer to have loose angles on one edge of the member, so that they can adjust to suit when assembling. This is a practice which does not appeal to the designer as it entails increase of weight, but it is a concession to workshop convenience which is sometimes unavoidable if undue tooling costs are to be avoided.

Simple sheet metal 'Z' or 'angle' sections are sometimes more suitable for rolling (or drawing) and cropping treatment, than for either routing or blanking. The usual criteria in such cases are the quantities required, the length and shape of ends. If the length is more than two feet, rolling is usually more economical but, if the ends are shaped in any way, blanking or routing are generally more satisfactory, because they eliminate subsequent trimming. For very small quantities folding of the blanked or routed parts may be suitable, instead of press bending, because of the cost of bending tools and of setting up presses. The same applies to very long parts, the pressing of which would require large and costly tools and occupy presses of a size more suitable to larger and more important jobs.

This question of economy in the use of equipment may also be an important factor in determining in the first instance whether a job should be rolled or bent, since rolling mills and drawbenches are usually less plentiful in a shop than other machines and, therefore, are likely to be well loaded. Should the designer decide to call for profiling around bolt holes, however, the shops have no choice but to blank or rout, but there is always a size below which the saving in weight does not outweigh the cost of manufacture—although the design and

TABLE IV

COMPARISON BETWEEN MACHINED AND FABRICATED COMPONENTS

A. Machined part (light alloy forging) for 1,000 *aircraft*—18 *components per machine*

	£	s.	d.
Operating time 37½ min. each (part automatic)	5,625	0	0
Setting time 15½ hr. per batch ...	77	10	0
Cost of tools	225	12	0
Cost of stamping dies	30	0	0
Cost of 18,000 stampings at 4/- each	3,600	0	0
Cost per component 10/7½ ...	£9,558	2	0

B. Fabricated part (M.S. sheet) for 1,000 *aircraft* —18 *components per machine*

	£	s.	d.
Operating time 65 min. each ...	9,750	0	0
Setting time, 3 hr. 44 min. per batch	18	13	0
Cost of tools	155	2	7
Cost of 18,000 sets of material at 11½d. per set	862	9	0
Cost per component 12/- ...	£10,787	4	7

C. Packing for use with B (L.A. sheet) for 1,000 *aircraft*—36 *components per machine*

	£	s.	d.
Operating time 3¾ min. each ...	2,250	0	0
Setting time 4½ hr. per batch ...	22	10	0
Cost of tools	11	8	0
Cost of 36,000 sets of material at ½d. per set	75	0	0
Cost per component 1/3¾ ...	£2,358	18	0
Total cost of *B*+*C* for 1,000 aircraft	£13,146	2	7
Net saving using *A*	£3,588	0	7

It is to be noted that there is also a saving in weight with *A*, as follows:—

A.	*Weight lb.*
1 off machined forging	0.30
For attachment to spar and rib:—	
4 off ferrules	0.015
2 off screwed rod	0.035
12 off solid rivets	0.022
12 off distance tubes	0.04
	0.412

B.	*Weight lb.*
1 off fabricated part	0.42
2 off taper packing (L.A. sheet) ...	0.05
For attachment to spar and rib:—	
7 off pop rivets	0.03
12 off solid rivets	0.01
8 off solid rivets	0.005
	0.515
Weight saving of *A* against *B*	0.103
Weight saving per aircraft (18 off) ...	1.854

production departments seldom agree on the location of this line of demarcation.

It will be seen, therefore, that shop equipment, layout and immediate loading, have a decided bearing on detail design; it is of no use to design for manufacture in six months time, something which could only have been taken on twelve months earlier or twelve months later.

The problem of sub-contracting, which is always something of a headache to the production departments, can sometimes be eased by the Design Department, by careful choice of design to make sub-contracting more feasible, with very little subordination of design quality to expediency. This idea needs to be followed with considerable restraint, however, otherwise it is likely to lead to a condition where the "tail wags the dog." One of the more serious disadvantages of the system is the fact that errors, either on the main contractor's drawings or in the sub-contractor's interpretation of them, are frequently not discovered until many parts are made and much time is wasted, to say nothing of financial loss. It follows therefore, that there is even more need for the thorough checking of drawings when work is to be sub-contracted than when it is going to be done in the 'home' shops.

Another important feature of design is the need to keep jobs simple. The main reasons are obvious, but it is also a fact that the simple design is usually the lightest. A motto of one well-known Chief Designer "Simplicate and add more lightness," is an axiom that should be in the minds of all who are concerned with design. Ingenious mechanisms are very attractive but ingeniousness can easily become the end, instead of the means, and is then the bane of production engineers, as well as being a fruitful source of unserviceability. "Ingenuity is preferable to ingeniousness."

Consistency in design is also a matter of some importance, more so with limited production than with large quantities. No factory can be laid out efficiently to cope with all kinds of work and a team of personnel cannot be experts in all branches of engineering. For these reasons the Chief Designer's policy should be clear cut and his staff should adhere to it religiously. This does not mean that a technique should be followed slavishly to the detriment of design efficiency, but that all work should be

controlled and directed by the head of the department. These remarks apply with particular force where the type of aircraft concerned is less than 15,000 lb. weight.

The tooling economy which can be effected by careful consideration in the detail design stage is particularly noticeable where blanked or routed plate fittings are concerned. On many occasions it is possible to modify dimensions slightly to make one blank serve for two or more entirely different fittings. This saves not only the cost of the second set of dies, or routing template, but also setting up time, because one setting up will suffice for the full quantity of both items. In addition to this, there is economy in storage space and stores accounting—one bin and one record instead of two. In order to exploit this idea to the fullest possible extent, however, it is necessary to have a satisfactory system of referencing, so that draughtsmen can check up rapidly on existing parts which could conceivably be used for the job in hand.

There is also the question of simplicity of shape. The cost of tools, particularly press tools, can be greatly reduced by considering the development of plate fittings. If this is done carefully, many odd and unnecessary bumps and corners can be eliminated. Furthermore, a more æsthetically pleasing shape will usually result. This is important psychologically and also because such shapes are more easily handled, less likely to cause cuts on the hands of operators, less abrasive to protective treatment on adjacent parts and are nearly always lighter. Also, both cost and time can be saved by making parts non-handed and this can be achieved in a surprising number of cases if a little care is exercised.

Admittedly, all these arguments apply whatever the quantity being manufactured, but they are more cogent where production is limited than they are for prototypes, where money is almost no criterion, or for large scale production where the expenditure is astronomic in any case and comparatively small economies have little or no significance.

Another important aspect of manufacture is the handling of components during assembly; local conditions such as floor space, available handling equipment, shop layout, etc., should all be taken into account when assessing the most suitable breakdown features of an aircraft or main component. Obviously the weight and functional characteristics of the part must not be prejudiced, but much can be done in the early stages to ensure the most efficient handling, by keeping single items to the smallest acceptable dimensions and arranging easy access for riveting, and so on. Lack of consideration of this last point is likely to lead to such things as unwanted access holes with their attendant stress and weight concentrations and marring of clean surfaces.

6. CONCLUSION

Summarising, it may be said that limited production can be a profitable and economic proposition if due care is exercised in design, tooling and manufacture and provided that liaison and co-operation exist between the Design and Production Department.

There is one departure from the accepted rules of economy, however, which is well worth considering, at least for military aircraft. This is the practice of building what are termed "pre-production" quantities. Even if the original order is only in the neighbourhood of 100, it is a good thing to build, say 25, on a 'no tool' basis. There are three main reasons for this. Firstly, it gets production under way quickly. Secondly, it gives the Production Departments an opportunity to assess the job and modify their staging arrangements as the work proceeds, before expending large sums of money and large numbers of man-hours on elaborate jigs and tools, which eventually may prove to be not the most suitable. Thirdly, it gives the Design Department and the customer an opportunity for minor improvements and equipment revision, without the risk of excessive scrap and delay.

It is essential that these 'pre-production' aircraft be built in the production shops and by production personnel and not by the Experimental Department, otherwise the whole value of the procedure will be lost.

Obviously, only a few of the ramifications of the subject of the inter-relation of design and manufacture can be dealt with in a paper of this kind, but it is hoped that the points raised will have created some interest and, perhaps, will afford some assistance in the assessment of future problems.

The views expressed are those of the author and do not necessarily align with the policy of the Hawker Company, to whom aknowledgment is made for assistance in the compilation of the factual examples quoted.

Aircraft in Agriculture

by

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INTRODUCTION

The application of aircraft to agriculture began in the 1920's; experiments in insecticide dispersal were made in Ohio in 1921 and a bulletin was issued by the U.S. Department of Agriculture on dusting cotton crops by means of Curtiss JN6H aeroplanes in 1924. Since then the idea has been developed, notably in countries of large area. In 1928, for example, crop dusting experiments were made in the United Kingdom but the results were not very encouraging because of the drift problem with comparatively small fields. The aircraft concerned were subsequently sold to the U.S.A. where this type of work rapidly became a commercial undertaking and has been steadily consolidated and improved.

Pioneering work was also done elsewhere and began about 1926 in the Union of South Africa with a number of D.H.9 aircraft. Until more recent years, however, progress in the general use of aircraft in agriculture and allied fields has not been outstanding but there may be great developments in this sphere in the near future.

As after the First World War, the 1939-45 War provided a stimulus to aeronautical engineering and to public (including rural public) airmindedness, but in the early 1950's the position, as far as the subject of this paper is concerned, is rather different from that existing thirty years ago. On the one hand it is being increasingly realised that development of world agriculture—and this implies both the improvement of present lands and methods and the creation of new productive areas—is vital, and on the other hand the evolution of highly effective agricultural chemicals in concentrated form has increased the potentialities of the application of such materials (especially liquids) from the air. Furthermore, the helicopter is emerging from the prototype stage.

From this point of view it is unfortunate that aeronautical development during and between the wars may be described as largely striving towards higher speeds and larger aircraft. The virtue of aircraft as a means of transport which is not dependent upon ground conditions has been lost behind the value as a means of ever more rapid propulsion from *A* to *B*. Agricultural operations require robust machines which are safe and manoeuvrable at slow speeds and low heights and which require a minimum of ground facilities and servicing. Helicopters may not prove to be the complete answer, especially if designers concentrate their efforts upon increased speeds at the expense of payload and the exploitation of inherent versatility. The introduction of gas turbines and the instability of world peace, however, will take development even farther away from the desired approach to fixed-wing aircraft and the progress of the helicopter is therefore of interest in agricultural circles.

Farming is a widely dispersed industry in which large areas have to be covered and, furthermore, it is likely that the inhabitants of rural areas will be the first to adopt light aeroplanes as a commonplace means of personal transport. This is a development which many have foreseen and attention by aircraft manufacturers to the needs of agriculture and the latent market it provides, could lay the foundations of great potentialities.

APPLICATIONS OF AIRCRAFT IN AGRICULTURE

It is necessary to approach the subject from a world-wide viewpoint since the degree of application of aircraft in agriculture is to some extent a function of land area and is least in small, highly developed countries.

*A lecture based on this paper will be given to the Graduates' and Students' Section on the 22nd January 1952.

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TRANSPORT

Transport is the primary function of civil aircraft and a major problem of the farmer and distributor of farm products. Furthermore, progress in agriculture involves the expansion of communications.

Many established farms and ranches are remote from good roads or railways but possess adequate landing and hangar facilities in their ground and buildings. A great advantage of an aircraft as a means of transport is that it can be used when surface conditions are impossible for ground vehicles. Obviously, in bad weather it may not be possible to fly, but conditions of atmosphere are of much shorter duration than those of the ground.

Speed is also an important consideration and as well as its especial value in emergencies, an aeroplane may be valuable in certain spheres purely as a time-saver.

The combination of speed and independence of ground conditions which the aeroplane affords the agriculturalist in personal transport has attendant psychological advantages. It permits a wider sphere of activities and also, by enabling the farmer to survey his land in its context of surrounding terrain, provides a broader viewpoint and a new appreciation.

In the transport of freight, aircraft allow wider markets of products which are subject to rapid deterioration; an example is the sale of Irish milk in Great Britain. Another example is the rapid transport of meat carcasses from remote inland areas to refrigerator ships in coastal ports, thus permitting the slaughtering of beasts in prime condition on, or very near, the ranch. Air transport is not at present so economically suitable for relatively heavy, non-perishable items but it is being extensively used in connection with livestock. The movement of animals over long distances is often best done by air in preference to a tedious journey or voyage; this is particularly the case with valuable pedigree stock.

The improvement of poor animal breeds is thus assisted by air transport. Maintenance of herds is of like importance and the use of aircraft to deliver food supplies on range lands in hard weather has recently been of the utmost value.

FARM SERVICES

The flying medical services built up in Australia are an excellent example of the way in which aircraft are of value for work not directly connected with doing the job, namely farming in remote areas, but important as regards human willingness to undertake it.

Veterinary services which can be quickly and reliably available are desirable in animal husbandry; in predominantly arable areas, weather being the great unknown risk, speedy provision of spares and repair facilities for ground machinery during the rush seasons is ably facilitated by aeroplanes.

The weather factor cannot be too strongly emphasised and some measure of weather control may be possible in the future; successful experiments in the scientific production of rainfall have already been made. Rainfall may be promoted on suitable occasions by, for example, the "seeding" of clouds with dry ice or similar agents and evolution of these processes is of importance in connection with the development or rehabilitation of arid regions.

In most countries the overall administration of agricultural industry is by a government department which may also operate advisory services in co-operation with universities and research establishments. Not only is the aeroplane of assistance for this work in dispersed territories, but it also enables a valuable picture of conditions in the area to be obtained. The first point, for example, is applicable in connection with pest control; the second is of particular importance to the soil conservation specialist.

SURVEYING

The erosion of soil by wind and uncontrolled water flow is a serious problem. Successful soil conservation practice is dependent upon the treatment and approach to the erosion problem being on an area basis. Aircraft are the most suitable means of obtaining a correct appreciation of any conservation district as one unit with individual farms in their proper context and therefore can assist in essential education in this subject. Air transport also facilitates the survey of areas to detect new erosion, inspect water-flow systems, measure the depth and water content of snow in the hills remote from the cultivated lands in order to determine watershed potential, and so forth.

Similarly, because a wide range of vision is afforded yet close inspection is possible, scope is provided by large agricultural development projects. In the first instance, aerial observation affords a useful picture of

the terrain and vegetation concerned and is logically followed by aerial photographs of specific localities to be used in the initial planning of the project and as base maps for the work of a ground party. Methods of photographic survey from the air have been highly developed and proved. Aerial photographs are used on a large scale by the Soil Conservation Services of the U.S.A. as base maps for field surveys.

Application of Agricultural Chemicals to Crops

Recent development of highly concentrated liquid insecticides, fungicides, defoliants and weed-killers has stimulated consideration of the most practical means of applying them over many different types of terrain and has aided the use of aircraft with their limited payloads.

In the deposition of insecticides, etc., by spraying, the aim is to produce a homogeneous and adequate coverage of the insects or vegetation to be treated, without shielding. The requirements are adequate and efficient coverage, timeliness of deposition and use of the appropriate chemical. Chemical development has now made very low dosage possible and aircraft possess an obvious advantage in connection with the second requirement, but the first requirement must be fulfilled.

Aircraft have distinct advantages over ground machines as prime movers for spraying apparatus. The work can be done more rapidly and can also be undertaken when the ground is very wet—a condition suitable for the spread of certain diseases and pests but unsuitable for the operation of ground machines—thus, incidentally, obviating any special need to drain irrigated areas. Speed of work is particularly important in the treatment of epidemics and because the best time for certain types of spraying is limited to a few hours a day. Furthermore, the treatment of tall crops from the ground requires special equipment if damage is to be avoided.

The major disadvantages of liquid deposition from aircraft are the difficulty in drop distribution control, the problem of drifting (especially with hormone or selective weed-killers) and the present-day cost.

"Dusting" is in effect the dispersal of a dry spray, *i.e.* using air instead of a liquid as the carrier, in which particles are deposited by impact or sedimentation. Before the introduction of highly concentrated sprays, dusts were more extensively used and applied by aeroplanes. An example of impact deposition peculiar to the use of aircraft is the laying of dust in front of a flying insect swarm. Dew is usually required to prevent dust removal from foliage and to give a lasting deposit for crop protection. Here again an aircraft is in use simply as a prime mover and has merits similar to those in connection with spraying but, although the turbulence created by a propeller can effectively force dust into crops, the material floats easily in the air movement created by the aircraft. Once dust has been carried up by air currents the time to settle is very long. Hence the problem of drifting.

In fumigation the problem of control is much greater and the use of aircraft in this sphere is limited. Ground fumigation machines normally hold vapour concentration in the vicinity of agricultural pests, by means of a mobile chamber, long enough to ensure mortality. However, there is scope for the application of smokes, produced, say, by vaporisation through injection in the aero-engine exhaust system. Condensation after leaving the exhaust produces a cloud and, although vapour concentration cannot be held in the vicinity of the insect and is subject to the incidence of thermal air currents, this method has been found valuable in the control of freely flying pests, for example, the tsetse fly. The use of aircraft for such work permits large areas to be treated quickly and cheaply.

Flat crops clearly require a more exacting technique than, for example, orchards. In the treatment of small, accessible areas where aircraft are in direct competition with ground machines as prime movers for equipment, they necessarily stand on their merits as a means of applying the powerful synthetics now available without any emphasis on their main advantage for large-scale operation, namely that without aircraft the job would not be done at all. A major problem in achieving results as good as those obtainable with ground machines is in forcing the chemical on to the undersurfaces of foliage. Thus the helicopter is especially suitable for spraying because the rotor downwash may be utilised to force drops or particles into vegetation. If the machine is flown within the ground cushion and the chemical is properly fed into the doughnut - shaped downwash, the crop

Fig. 1. Bristol " Freighter " distributing lime.

interference to the air/chemical stream gives a high dynamic catch and a deposit on most, if not all, foliage surfaces. Rotor downwash can also be used to dry orchard fruit after rain, or to prevent frost by drawing down warm air to tree level.

Sowing of Fertilisers and Seeds

It is not suggested that aircraft can compete with ground machinery for the precision placement of seeds and fertilisers in highly developed agricultural practice, but wherever the degree of precision is relatively less important than execution, the use of aircraft can be effective .

The greater the area to be covered the more economical are aircraft likely to be. In certain cases, even over small areas the operation of ground machinery involves a greater expenditure of effort and money. For example, the advantage of an aeroplane which is independent of the unfavourable surface conditions associated with sowing rice is obvious. Seed may also germinate in wet or recently waterlogged land before the latter is in a condition to support machinery.

The application of fertilisers is a major factor in the improvement of poor range and hill lands and the use of aircraft as a means of applying seed and fertiliser to areas of this type has distinct possibilities. The advantages of aircraft are again rapidity and extensiveness of work and ability to undertake the operation without undue effort. They provide the only practical means of applying materials to hill lands on anything like a large scale. Light aircraft may be employed when the rate of application per acre is low, *e.g.* with seeds, but for high rates per acre, for instance with lime, larger aircraft are normally required.

The emergency treatment of land also affords scope for aircraft. Soil drift may be checked and the rehabilitation of eroded lands assisted in the first instance by dispersal of pelleted seed to fix the soil and promote aggregation.

The main disadvantages of aircraft for the simple distribution of seeds are difficulty of even distribution and probable relatively low germination rate of bare seeds due to inadequate coverage.

Aircraft and Performance Requirements

Before particular consideration is given to the problems involved in the uses of aircraft for crop culture, the types of aircraft and the performance required from them will be considered in general terms.

The major factor affecting selection of any aircraft is operational suitability and it will be realised that in agricultural operations a high degree of serviceability is of considerable importance.

Small, single-engined (unsupercharged), fixed-wing aircraft are likely to play a major part in the application of aircraft to agriculture for many years. The most suitable type is probably of " family size " and capable of carrying persons, freight or special

equipment plus a load of material. Versatility and easy interchange of equipment are important factors.

The performance requirements in both single and twin-engined aircraft for agricultural work are in some cases contradictory and, as usual, compromise is necessary. Perhaps the major considerations are manoeuvrability at low heights and speeds, a low safety speed (implying a low stalling speed), ease of maintenance and reliability. The shorter the take-off and landing runs, compatible with payload, the better, and it is particularly necessary in the design of single-engined "flying jeeps" that they be as easy to fly as possible, *i.e.* foolproof. Good vision forward and down is desirable, and owing to a possible high incidence of cross-wind landings, strong landing gear is advisable.

Extensive use of the helicopter would require certain improvements on average present-day design. Firstly, a simplification of pilot's controls and improvement in stability, easier and less frequent maintenance and a longer life of working components would be necessary. A minimisation or, if possible, elimination of the danger height range in the event of single-engine failure, would be desirable. In agricultural operations there is little air room.

The operation of aircraft of all types in agriculture necessitates the installation of air speed indicators which are accurate at low speeds and of altimeters (possibly of the contacting type) which are highly accurate at low heights. The purpose of aircraft in these applications is primarily to do an agricultural job of work: the function of flying is secondary. Navigation as well as flying control therefore, needs to be as simple as possible and at least short range radio should be fitted. Navigational aids are dependent on the work to be done but radar offers distinct possibilities in some instances and the possibilities of piloting by remote control from the ground should not be discounted.

Having outlined briefly the scope offered by the world's agricultural industry to aircraft operation it is now proposed to discuss in some detail the most direct uses of aircraft in farming, *i.e.* as a means of dispersing various materials. This involves an aircraft being used for carriage of the material and at the same time as a prime mover for the dispersal equipment: the primary function may be either.

DEPOSITION OF MATERIALS FROM AIRCRAFT

The required grain or drop size of solids or liquids applied in agriculture is governed by the type of seed or fertiliser in the first case, or upon the size and type of insect, or of foliage to be covered, in the second case. There are obviously wide variations in size of seeds and chemical fertiliser granules and there are also wide variations in the required drop size of liquids, according to the job to be done, the liquid used and the climatic conditions. The spraying of locusts, for example, requires some 5 to 10 drops/in.^{2}, while for smaller insects on crops a finer spray is usually required, possibly less than 100 μ (0.1 mm.) drop diameter.

The technique of application from the air therefore must be in accordance with these agricultural considerations and is further complicated by the density of the material as well as the grain size.

CONSIDERATIONS IN THE FREE EMISSION OF LIQUIDS FROM AIRCRAFT

If a liquid is poured out of a fixed-wing aircraft it is immediately shattered into drops by the relative motion between aircraft and the air medium. The size range of the drops so produced is dependent upon the viscosity and surface tension of the liquid and the speed of the aircraft relative to the air into which the liquid is introduced. The influence of the aircraft speed will be affected by slip-stream and air turbulence in accordance with the point of liquid exit on the aircraft structure. Once remote from the aircraft, the liquid drops produced in this way will be controlled by wind speed and direction. Their downward terminal velocity and its dependence upon drop size will give rise to a "sheet" with the largest drops below, drifting on the wind. Hence, if the aeroplane were flying across wind the ultimate result would be a wide band of deposit on the ground with the larger drops on the upwind edge and the smaller drops downwind.

The distance the drops are carried by the wind is proportional to wind speed and time taken to fall from the height at which they become controlled by wind. The time taken to fall is determined by aircraft height (for any one method of liquid emission) and the terminal velocity of the drops: hence the distance travelled varies as the product of height and wind speed. This product

determines the drop distribution on the ground according to size.

The "drop spectrum" on the ground or frequency distribution of drop sizes is largely a characteristic of the liquid but is affected by aircraft speed.

Large-scale "spraying" by aircraft

There are two known methods of spray distribution from aircraft: the aircraft flies at a height of 100 to 500 ft. and the liquid is freely emitted, or it flies as low as possible and the liquid is forced down by pressure-fed nozzles. The forcing method is more generally applied over small areas, whereas large-scale operations usually require use of the free-emission method with technique based on the foregoing considerations.

If the product of aircraft height and wind speed is fixed and the drop spectrum is known, then the volume of liquid per unit ground area, *i.e.* the "deposit density" at any point, can be calculated and plotted against distance from the aircraft at the time of emission. This applies whether the aircraft is flying parallel or at right-angles to the wind direction; only these relationships between aircraft and wind directions are considered in this paper. In practice the required deposit density is chosen and the rate of liquid emission from the aircraft is known: hence, if the aircraft is flying at 90° to wind the theoretical swathe width of deposit (per run of the aircraft over the area) can be obtained. Alternatively, if the rate of emission from the aircraft can be varied, then a convenient swathe width can be chosen within limits and the emission rate set to give the required deposit density. As deposit density varies with distance from aircraft track, the degree of swathe overlap required to approach constant deposit over the area can also be calculated.

Emission of liquid from the aircraft is in its simplest form by gravity feed through a pipe of fairly large diameter, with the rate of emission governed by the head due to liquid volume and any pressure difference between the tank and the outlet. The variation in emission rate with a fixed orifice outlet, due to decrease in head as the tank empties, leads to waste of liquid, and variable diameter outlets (*e.g.* iris diaphragm control) are preferable and can be automatic in operation. The tank content in relation to rate of emission governs the ground area sprayed per aircraft trip and the actual operating time between landings to refill.

It is preferable that steady wind conditions obtain during "spraying" by this method and there should be a minimum of atmospheric turbulence, particularly of up-rising air currents; temperature inversion in the early morning may assist deposition. These same considerations apply to a lesser degree when the liquid is distributed by way of pressure-fed nozzles, but it is advisable in either case that the mean wind speed should be less than 10 m.p.h. The forced-feed system of liquid emission, with which adjustments in number and size of nozzles and of pressure are possible, has found favour in the U.S.A. for large-scale operations with twin-engined aircraft, but at present it is generally confined elsewhere to relatively small areas and single-engined machines.

Small-scale application of liquids

In this sphere there is a need for greater accuracy than in large-scale work and this has resulted in the use of pressure-fed nozzles mounted across the wing span: in other words, the aircraft acts simply as a prime mover and carries apparatus similar to that used with ground machines. It flies very low, just above crop height, and swathe width is more easily defined. Such technique raises greater problems of aircraft safety, pilot skill and swathe demarcation.

Unstable air conditions are adverse to the deposition of small drops and in the portion of the atmosphere close to the ground there are usually only short periods of each day during which stable air exists. On the other hand, large drops reduce the efficiency of the spraying operation.

If the free emission system were used with helicopters the liquid would have to be released outside the rotor disk: if it were released below the rotor disk a narrow swathe would result. Hence pressure-fed nozzles mounted on a boom are used. An incidental danger, particularly in the application of dust from helicopters, is that if the outlets are not properly placed, *i.e.* protruding into the annulus of the rotor downwash, a quantity of dust may be lifted by eddy current from the calm area under the aircraft into the vicinity of the engine. Accidents have occurred in this way.

Some relative merits of helicopters and fixed-wing aircraft for small-scale operations

Fig. 2. Hiller 360 Helicopter engaged in spraying for weed control.

are briefly as follows (the use of rotorcraft for large-scale work is not considered). In the first place, fixed-wing aircraft are normally operated at weak mixture setting and this may not always apply to a helicopter when travelling relatively slowly with full load. The vertical ascent and hovering performance of a helicopter at full load is adversely affected by flying above pressure cushion height and is reduced with height above sea level. Hence, helicopters are sometimes not as suitable as fixed-wing aircraft for operations over high foliage canopy or from high altitudes. However, the helicopter does a better job of spraying from the agricultural point of view, confines deposit more accurately and is of considerable value when the flight track is torturous owing to gullies and so on. At present its use is limited by a higher initial cost and higher cost per flying hour which, in conjunction with a lower forward speed, results in a higher cost per acre treated.

The slipstream of a helicopter when hovering within the ground cushion is bell-shaped with an annulus cross section; increase of forward speed progressively produces a more horizontal downwash due to the change in blade pitch. As the downwash characteristics are affected by changes in pitch or azimuth control, it is preferable to have a minimum of alterations when spraying and gusty conditions are unfavourable. When a helicopter is flying forward, the slipstream annulus is elongated rearwards and a similar parabolic effect is produced by wind speed. Hence, the slipstream form brought about by the respective directions and velocities of the machine and the wind must be considered. If the aircraft is flying across wind the spray deposit will be roughly along the resultant of the two velocities.

Interference of the loaded downwash by the crop gives a high dynamic catch. The introduction of liquid from pressure-fed nozzles into the forward part of the slipstream has been investigated but most commercial machines have spray booms fitted on either side of the waist of the aircraft, *i.e.* lateral to the centre of gravity. This may not continue to apply to multi-rotor systems which, because of greater stability and reduction in control movements, should also decrease the problems in flying technique when spraying.

Application of Smokes

In this method of application of insecticides and so on (*e.g.* D.D.T.), air is charged with material and therefore falls massively. The normal method of production of smokes is by vaporisation of solutions by injection in

the aero-engine exhaust system. Wind speed and aircraft height should be a minimum and difficulties in introducing smokes into ground pockets have led to the equipment of helicopters with similar smoke generators, but the consequent increased engine loading introduces complications which do not arise with fixed-wing aircraft.

Dusting

The main function in dusting is to produce a cloud of solid particles which are deposited by impact or sedimentation from a low height. The problems of distribution are similar to those of free liquid emission (except in so far as particle size is concerned) and dispersal of smokes. The dust is normally fed into the aeroplane slipstream, often accelerated by a venturi, from a well-agitated hopper.

With single-engined aeroplanes it has been found that a spiral and downward motion is imparted to the dust cloud. Under good atmospheric conditions the major fraction of this dust is intercepted by foliage directly in the stream before any eddy-diffusion starts as the slipstream influence fades. Very small particles may tend to flow round obstructions and avoid this direct filtration and thus with fine dusts there is often a poor catch and a high risk of drifting with the wind. The underlying problem with dusting is the very slow rate of settling of particles which become "suspended" in air, and particularly so with fine particles which may drift and cause damage to other crops some distance away. Helicopter installations have reduced this disadvantage, which is by no means non-existent with ground machines.

Considerations in the Free Emission of Solids from Aircraft

The term "solids" refers to seeds, chemical fertilisers and baits. The problems of deposition from aircraft are similar to those involved in the free emission of liquids, but the grain size of the material is not influenced by the relative motion between aircraft and air. Grain size and density of material vary considerably and the variations to be found in a mixture of seeds, or of seed and fertiliser, for example, give rise to a number of problems. The terminal velocity and its variation with size and density, at constant wind speed, will give a shorter distance between ground deposition and aircraft at the time of emission for wheat seed than for, say, grass seed. The dispersal or "winnowing" effect with mixtures is thus similar to that found with free liquid drops.

In the dispersal of one material of more or less constant size and density, the required deposit density can again be obtained by variation of swathe width (*i.e.* aircraft height) and rate of emission but is more important with seeds. It is necessary with very light seeds to operate at minimum aircraft speed and height and under steady wind conditions of minimum force.

The problems in deposition of solids can be simplified by artificially creating uniform grain sizes and weights, with an increase in size and weight for light seeds or fertilisers.

Large-scale Sowing of Seeds and Fertilisers

From the agricultural aspect a disadvantage of sowing seeds from the air is the risk of a low germination rate, especially in low rainfall areas.

The problem of germination as well as of deposition can be reduced by "pelleting" of seed or fertilisers, a process particularly applicable to mixtures. Progress has been made in the consecutive coating of seeds with clay, fertiliser, moisture-retaining substances, insect and rodent repellants and so on, to produce uniform pellets and also in the production of compound fertilisers in pellet form. The increased size and density of such pellets, compatible with distribution requirements, assists ground penetration and thus the germination of seeds, as well as increasing the germination rate by virtue of the coating itself. Also, in conjunction with the production of uniformity, it reduces the effect of wind speed on distribution and therefore decreases the problems of deposition as compared with liquids.

Swathe width and deposit density at constant emission rate are largely functions of aircraft height alone, even when flying across wind. On the other hand, the risk of excessive overlap and other sources of waste makes accurate technique even more desirable. When an aircraft is engaged in the deposition of seed pellets or fertiliser it is probable that each load will be dispersed in a short time; hence, it is often preferred to fly into wind during each run.

Trials have shown that there is no mechanical or ballistics problem in this connection which does not have every

possibility of being overcome, for example by uniform pelleting, but it will be realised that any such processes designed to reduce the atmospheric influences on distribution bring about a reduction in effective rate of work. Equipment has been considered, and in some cases developed, which is comparable to the use of spray booms for liquid deposition in that means are used to spread the material at the source, namely at the aircraft, and to promote uniformity in deposit density over the swathe width. A further point is that certain materials, for example burnt lime chips, which are reasonably uniform in particle size when at the original low moisture content, are subject to the effects of atmospheric humidity.

SMALL-SCALE SOWING OF SEEDS AND FERTILISERS

The additional problems in small-scale operations are to distribute the material within the firm boundaries of a specified area, to maintain at the same time aircraft stability and to distribute seed at least as well as if sown by hand. The last point arises because the aircraft is more in competition with ground machinery. Thus, although some difficulties inherent in free emission are simplified by small-scale operation, the greater accuracy desired and the necessary lower aircraft heights, with consequent narrower swathe widths, have again led to the development of apparatus for "spread" emission.

CONSIDERATIONS IN FLYING

An essential in the application of materials from aircraft which has not so far been mentioned is a system of ground demarcation.

On the completion of each run over the area to be treated, the aircraft returns to reload or turns and starts a parallel run in the opposite direction. In either case, unless the pilot can see, during his next approach, the deposit from his last run it is obvious that some system of marking or flight control by a ground party is necessary. In the simplest form, smoke signals may be used for relatively high flying operations and brightly painted vehicles or flags for lower heights. The ground party are briefed on the calculated swathe width, *i.e.* movement of the markers between each run, and may be provided with vehicles having suitable odometers.

Some detailed discussion of the merits of flying parallel or at right-angles to the wind direction must now be made. With spraying by the free-emission system, highly-concentrated liquids are used and low deposit densities are required; the aircraft load will often be sufficient for a number of runs over the area. If the aircraft flies into wind at any one height, then a relatively narrow swathe width will be obtained and a low emission rate will have to be used to achieve the low deposit density required, partly because of a peak below the aircraft track with lower densities on either side. Furthermore, after each run the aircraft will have to make a non-useful journey to the other end of the distribution area before starting the next spraying run, unless a return run is made with the wind. In the latter case, unless the wind speed is very low, the additional calculations and sources of error in execution will increase the difficulties of both pilot and ground party. A wider swathe width can be achieved by flying at a greater height, but this increases the influence of wind and the difficulties of accurate deposition. A wide swathe is best achieved by flying at 90° to wind with a higher emission rate, more useful runs per aircraft load and therefore lower cost, in spite of difficulties in flying a straight course.

With pressure spraying over small areas a similar conclusion may be reached. For example, with a helicopter a very low wind speed may permit spraying parallel to wind in both directions; but if the wind speed approximates to the desired speed of flight then the helicopter must fly into wind only, or at 90° to wind. The latter method is often preferred because of a lower cost per acre treated, although the accuracy of deposition will be less, and it has a further advantage in that turns at the end of each run can be made into wind. In the treatment of small, definite areas such as individual fields it is desirable, however, to fly parallel to the longest side in order to minimise the number of turns.

In the dispersal of a seed mixture with which there is a variation of particle size and density, the method of flying across wind may be preferred because a constant deposit density of the *mixture* can be obtained more easily. However, whether the aircraft flies into, or across, wind, extra runs will have to be made over certain edges of the area boundary to complete distribution.

The low deposit densities in relation to aircraft load, which often apply in spraying, seldom apply with solids and hence the aircraft load may be sufficient for only one run over the area. In this case the method of flying into wind, which is obviously preferable from the pilot's point of view, is usually adopted. This is particularly the case in the distribution of pellets or of fertiliser (including lime) with which high deposit densities (by weight) are required and a peak in deposit density beneath the aircraft track with "troughs" between runs is not of such consequence.

Whether the aircraft flies at 90° or parallel to wind therefore, is governed by the type and circumstances of the operation; it is for this reason that the subject has been left until this stage of the paper. In general, flying at 90° to wind is most common in spraying operations and flying into wind is most common for the dispersal of solids.

When an aircraft is flown across wind the simple methods of ground demarcation previously mentioned are suitable because the markers can be on the beam and within the pilot's view throughout the period required. Given accurate navigation, markers at only one end of the area may suffice; there are also the possibilities of distinctively coloured materials and of a system (most applicable to smokes and dusts) whereby two or more aircraft follow each other in wide echelon.

The pilot of an aircraft flying parallel to the wind is unable, with the vast majority of aircraft, to see ground markers right up to the moment at which emission should be started or stopped because his downward vision is restricted. In this case the only suitable method of control has been found to be by short range, ground-air, two-way radio from mobile ground personnel.

Without an efficient method of ground demarcation—and even with it—the onus on the pilot is considerable and when there is no other crew the controls of emission equipment need to be such that full attention can be given to flying.

In small-scale operations the problems are increased from the actual flying aspect by small areas and very low heights. Crop treatment of this sort appears to be considered by insurance companies as not a good risk. In many cases a high degree of pilot skill is required if high standards of efficiency and safety are to be attained and there will always be a large number of landings and take-offs per day. Methods of ground demarcation are simplified by small-scale work, orchard treatment in particular, but on the other hand, the pilot is subject to the effect of a monotonous job with consequent increase in fatigue. Operation of helicopters on small-scale work in the future will probably be advantageous from these points of view.

The essentials in deposition of materials from aircraft over an area of land are that a constant height, constant speed and steady track be maintained on each run, that material emission be started and stopped in accordance with the boundaries of the area and the wind direction and speed, and that reloading or the sequence of climb, turn, approach and flattening-out at the end of each run be executed quickly and accurately.

EQUIPMENT FOR APPLICATION OF MATERIALS FROM AIRCRAFT

In the design of dispersal equipment to be installed in the aircraft, performance is the first consideration but interchangeability and provision for emergency dumping are important factors.

The simplest apparatus for dispersal of solids or dusts is a "spreader" consisting of a hopper, valve and venturi outlet. A typical installation for a small aeroplane has a hopper mounted in the front cockpit and fitted with two agitators driven through reduction gearing from a small propeller mounted in the slipstream. A sliding gate valve controls the feed to a venturi which has its maximum point of constriction directly below the valve opening and is formed by a small aerofoil under the fuselage. To give a wider swathe, venturi outlets have been made fan-shaped, or divided and spread to form two outlets.

Equipment of this type has been enlarged for use in twin-engined machines and the problem of irregular emission rates at low hopper contents has been reduced in one instance with a twin-engined aircraft by a design intended primarily for fertiliser distribution and having a number of hoppers. This enables a more constant discharge rate to be obtained by emptying the hoppers in sequence, or they can be filled with different materials to distribute a mixture, or used together when high deposits are required.

Replaceable hoppers with outlets along their length have also been installed in the

bomb or torpedo bays of ex-military aircraft and have the advantage of a short ground running time. The simple method of discharge through a gate valve, with or without acceleration from a venturi, is cheap and has also been used for seed dispersal.

Spinner disks, although more often used for heavy suspensions and emulsions which cannot be passed through nozzles, have also been used to give increased swathe width of solids. This more expensive equipment consists, for example, of a pair of concave steel disks mounted slightly apart on a common shaft driven from a small propeller; material fed through the centre of the foremost disk is thrown out from the peripheries by centrifugal force and the air flow due to aircraft speed also helps to break up heavy fluids. Any means of ejection to increase swathe width should be designed to obviate tail reaction.

A further design on the spinner principle is a driven rimless wheel; through its horizontal hollow spokes pelleted seed is fed and thrown out by centrifugal force. Pneumatic ejection also appears to warrant investigation and may assist in control of rate of discharge.

A typical design for generation of smokes is an extension of the exhaust piping of a single-engined fixed-wing aircraft to a point in the rear of the cockpit where the solution to be atomised is injected into a venturi constriction designed to give optimum particle size.

Simple emission tubes for liquid dispersal have gravity feed from a tank (fitted with breather tube to reduce variation in rate of flow) to a pipe, or pipes, protruding through the boundary layer under the fuselage with the apertures facing rearwards. Each outlet diameter is often variable by iris diaphragm and may be placed in a venturi tube to accelerate air flow and produce finer drops.

The simplest forms of suspended spray booms are also gravity fed. A boom is suspended below the wings across part, or the whole, of the aircraft width and liquid emerges from holes drilled at intervals. A "breaker bar" is shaped around the upper rear segment of the boom to give a venturi effect and thus to increase the air speed over the outlets. The released liquid impinges upon the lower edge of the breaker bar and forms a fine spray to which a "roll" is imparted, at the outer ends, by the wing-tip vortices.

A typical pressure-fed boom installation is made up as follows. A centrifugal pump driven from a small propeller, or by the aircraft engine, is placed in a hydraulic circuit between a tank and a boom having flexible connections and fitted with nozzles at intervals along its length. Each nozzle is provided with a check-valve to prevent drooling after cut-off and the circuit also includes an adjustable pressure relief valve which discharges into the bottom of the tank to promote agitation. Output and degree of atomisation are varied by the pressure and by the type and number of nozzles; the direction of nozzle discharge relative to the air flow has formed the subject of some research. It has been found that streamlined suspended

Fig. 3. Auster "Aiglet" equipped with spray boom and propeller-driven pump.

booms do not affect aircraft flying characteristics appreciably but, as an alternative, nozzles have been fitted at wing tips and supplied by piping through the wing section. Advantage is taken of the wing-tip vortex to give a wide swathe and twin nozzles having a lower rate of discharge may be fitted in the aircraft tail.

In twin-engined aircraft installations the pump is usually powered by a separate petrol or electric motor. The insecticide tank itself may be suspended below the fuselage of small aircraft and in one installation, for direct emission of liquid under gravity feed, a "bomb-bay" tank supplies a smaller tank fitted with a float valve to give a constant head during each run.

OPERATION AND MAINTENANCE OF AIRCRAFT

Agricultural operations such as spraying or sowing entail, as compared with more conventional uses for fixed-wing aircraft, a large number of short sorties per flying day. An aircraft engaged on this type of work will be operated at its weak mixture cruising speed during the greater part of the time and therefore it may not be necessary to carry a full fuel load. This will depend upon the type of operation; for example, if the aircraft's load of material is dispersed in one run it will be necessary to carry less fuel than if the load is dispersed during a number of runs at a lower distribution rate.

In a large-scale undertaking over remote and undeveloped terrain there are two possible methods of organisation. Aircraft engaged in such work can be operated from one central aerodrome or from a number of forward landing strips. The central aerodrome is undoubtedly most satisfactory from the maintenance point of view and may be the only system possible if the terrain to be treated is hilly or wooded. There are further advantages in that stocks, facilities and personnel can be concentrated in one place, but a disadvantage is that the aircraft will have a relatively long flight to and from the distribution area. In other words, the ratio of total flying time to distribution time will be high, fuel consumption per unit area treated will be high and the rate of distribution, expressed as area per flying hour, will be low.

On the other hand, operation of aircraft from temporary landing strips located near each distribution area will give a higher rate of work and lower ratio of total flying time to distribution time provided, and this is the essence of the matter, that adequate organisation of supplies and servicing can be set up. Operation from a number of dispersed landing strips as opposed to operation from a central aerodrome requires a larger, dispersed organisation. In some cases the mobile nature of the work will present considerable problems in the transport of personnel and materials between landing strips and from a base to support such a method, as well as difficulties in communication and co-ordination. It is possible that in certain circumstances more flying hours and effort will be expended in this way than is saved by the shorter flying hours per acre treated, of the aircraft actually distributing material.

Choice of the organisation system naturally depends on the types of operation, terrain and aircraft available. In general large-scale operation by twin-engined aircraft is best suited by a central aerodrome and with single-engined aeroplanes or rotorcraft, for treatment of "pockets" of land and small areas, temporary landing strips are preferable. Taking the economic range of single-engined aircraft engaged in the dispersal of agricultural materials as being a maximum of five miles from a landing strip, it will be seen that this is sufficient to deal with marginal land but that any hilly hinterland beyond requires the use of twin-engined machines.

With single-engined aircraft operating over short transport distances the machines are being used primarily for elevation and distribution of the material and efficient operation depends therefore upon rapid reloading; chock-to-chock times as low as three minutes have been recorded. With aircraft operating up to, say, fifty miles from base, payload is probably the more important factor as the aircraft are also being used as a means of transport. A high ratio of total flying time to distribution time can be afforded if the cost of delivery to the area by ground haulage would be prohibitive: fertiliser, for example, has been delivered direct from the factory airfield to the land requiring it.

The height of the landing ground must also be considered: a central aerodrome may be sited at a low altitude although aircraft are operating over hills, whereas forward landing strips would be at higher altitudes and impose limitations to take-off which might

seriously reduce the payload, especially of helicopters.

In addition to aircraft maintenance, the equipment for material distribution will also need cleaning and servicing. There may, however, be longer non-flying periods, owing to weather, than is found in airline flying under modern techniques and there are certain agricultural operations which are best done during short periods of the day, thus allowing adequate time for maintenance work. Weather loss is difficult to overcome, except so far as consideration of meteorological factors at the pre-planning stage can be of assistance, but overhead costs when a short flying day on agricultural work is necessary might be reduced, where possible, by combining two operations, for example, fertiliser dispersal and surveying.

Individually owned aircraft of the family capacity type will usually be flown from unprepared landing grounds by amateur pilots; therefore they must be of robust construction. Daily servicing needs to be within the capabilities of an average farmer car owner, and maintenance, apart from major overhauls, should be within the scope of an average garage mechanic after instruction. Although there is a particular need for attention to its easier maintenance, an asset of the helicopter is that its mechanisms are comparable to those in many means of surface transport.

The operation of single-engined fixed-wing aircraft and rotorcraft which are not integral parts of a large-scale organisation is either as individual units or in small fleets. Individually they are part of the farm equipment: in fleets they are usually operated on a contract system and the organisation is governed by the routine of work undertaken by the contractor on a profit or loss basis.

COST

It is extremely difficult, if not impossible at this stage, to assess the cost of operating individually owned aircraft in agriculture, as this depends greatly upon specific circumstances and the interchangeability of equipment. It is generally acknowledged that costs must be reduced if progress is to be made.

The cost factor in large-scale operations (which are visualised as being normally done by State or co-operative organisations) can be reduced by intensity, but then the total cost of the work may be prohibitive. However, operations may be undertaken in which the immediate cost consideration is of minor importance, compared with the value of the results; value, that is, to humanity.

Commercial (contract) operators of single-engined aeroplanes in the U.S.A. have been charging in recent years between three and six cents per lb. per acre for the distribution of material only, in other words 30 to 60 cents for a dosage of one gallon or 10 lb. of insecticide per acre. The cost of insecticidal material must be added to this charge. In South Africa D.D.T. smoke dispersal against the tsetse fly has cost, overall, 3s. 9d. per acre, *i.e.* 1s. 3d. for distribution and 2s. 6d. for D.D.T. Charges as low as this are only achieved by constant use of the aircraft and personnel, usually by treating a large area in one neighbourhood and then moving on. With helicopters the costs are higher but as some crops in highly cultivated areas can stand spraying charges of £3 or so per acre, this is not now so prohibitive.

Low costs have also been achieved in large-scale operations. For example, the spraying of 130,000 acres in the U.S.A. with a dosage of one gallon per acre from a Dakota aircraft carrying 900 U.S. gallons of insecticide, cost one dollar per acre.

Any estimate of operating costs must be based on performance data, little of which is available in the agricultural sphere, and space does not permit the calculation of a hypothetical case.

However, taking a twin-engined aircraft engaged in the dispersal of insecticide at the rate of two gallons per acre and having a tank capacity of 500 gallons, and assuming that each sortie is of one hour duration, half of this time being spent in actual emission, then for flying intensities of 500 and 1,000 hours per annum, the cost per flying hour is estimated as £25 and £15 respectively and the cost per acre treated (including insecticides at 5s. per gallon) is estimated as 12s. and 11s. respectively.

With a single-engined fixed-wing aeroplane the cost per flying hour is estimated as from £5 to £10 and it has been shown under good conditions that an aircraft of this type is capable of covering some 25,000 acres a year at a distribution rate of 2 cwt./acre.

Obviously, a greater accuracy of dispersal achieved by the employment of expensive ground control equipment entails a higher cost and in future years the applications of aircraft to agriculture will depend to some extent on success in experimentation to

increase efficiency and, at the same time, to reduce costs. The greatest stimulus which can be given to the use of aircraft is the same as that applying in the private owner field—a reduction of costs.

FUTURE

It is suggested that the application of aircraft to agricultural operations is best achieved in three inter-related forms. Firstly, single-engined, fixed-wing monoplanes of "family size" and with easy interchange of equipment will undertake individual requirements and localised tasks. Secondly, fleets of single-engined aircraft, and possibly helicopters, will be intensively operated by agricultural contractors on scheduled, routine seasonal work in the normal way. Transport aeroplanes will also be flown on agricultural work by airline companies. Thirdly, twin-engined aircraft with specialised equipment will be employed on large-scale operations, probably by Government organisations, in conjunction with smaller machines to deal with "pockets" and marginal areas.

The stage of development reached in large-scale application seems comparable to that of aerial survey a decade ago and it may well be that its progress can be assisted by a measure of integration with aerial surveying, to reduce costs in both cases by the joint use of ground control equipment and by higher flying intensities per aircraft under similar operating conditions.

In all three forms of application there is a need for specific field trials of aircraft and installations and of refinement in operating methods. There is also a need for attention to aircraft design and performance requirements for these applications on the part of aeronautical engineers. In the U.S.A. the successful activities of contractors and others have prompted the aviation industry to design and produce a number of aircraft specifically for agricultural use and it is encouraging to note that at least two major aircraft companies in the United Kingdom are devoting some attention to agricultural needs.

ACKNOWLEDGMENTS

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*The Application of Plastics to Aircraft**

by

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1. INTRODUCTION

The object of this paper is to indicate briefly the suitability of plastic materials to aircraft construction and design. Attention is focused on the mechanical properties of the materials, and the types of design. At the same time, the general engineering worth of the materials under service conditions is indicated.

Research and development of plastics within the past few years has presented to industry a whole range of new constructional materials. The properties of these new materials vary widely, and in many cases surpass those of metal and wood. It is because of this flexibility in the available properties, or combination of properties, that the greatest advantages can be obtained in the search for highly specialised materials. The material can be tailored to meet definite and exhaustive requirements, thus distinguishing itself from the classical aircraft materials which are more limited in their flexibility. Although it is not suggested that plastics are a universal panacea for all production troubles, their use has solved many problems.

The raw materials for plastics are fairly easily obtained, and are abundant in Britain —fats (glycerines), milk (casein glue), coal (phenol and formaldehydes), and wood pulp (cellulose). They are reasonably cheap to produce. The fillers are more difficult to obtain, being asbestos, fibre glass, mica and wood, and they increase the cost of a structural plastic to six or ten times that of a similar weight of steel.

*One of the winning papers of the 1951 Junior Members' Papers Competition of the Bristol Branch of the Royal Aeronautical Society.

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NOTATION

E = Young's modulus
I = moment of inertia
ρ = specific gravity
G = shear modulus
P = compressive load per unit length
l = length of panel
h = thickness of sandwich (centre of plate to centre of plate)
t = thickness of plate
E_1 = Young's modulus for the filling in the direction of loading
E_3 = Young's modulus for the filling normal to the plate
ρ = density of plate material, ρ_F = density of filler material } (In Appendix)
b = (unsupported) panel width
ν = Poisson's ratio for plate material
μ_{31} = shear modulus of filler
W = weight per unit width of panel
R = fuselage radius
M = bending moment
τ = shear stress
f = direct stress
a = length of side of square cross section of strut
a', wa' = lengths of sides of rectangular cross section of strut

2. GENERAL DESCRIPTION OF LAMINATED PLASTICS

By means of their response to temperature, plastics may be divided into two main types —thermo-plastic and thermo-setting. A thermo-plastic type is one in which softening with rising temperature is a reversible process; that is, a product hardens on cooling, but may be softened by heating an indefinite number of times. A thermo-setting material is one which is changed, by the application of heat, into a product which cannot

subsequently be softened by heating. The thermo-setting plastics are much to be preferred from a structural point of view and will be considered here.

After the application of heat and/or pressure, the "cured" sheet becomes insoluble and infusible, and can be drilled or machined, and generally worked in a similar manner to metals. The result is a wide range of light, durable materials of almost the same strength as metals and excellent engineering properties.

The structural plastics differ greatly from the plastics of such things as cigarette ash trays or Perspex windows. This is because the pure unfilled plastics are weak in tension and shear. Their strength, in fact, is achieved from the bonding of long chains of molecules by means of inter-weaving and cross-linking. Now it has been discovered that, by the introduction of fillers, this bonding is greatly enhanced, and the mechanical properties improved. Many types of filler are used, and each filled or laminated plastic has its own characteristics, closely following those of the filler and the parent plastic. For example, for good temperature responses, asbestos fibres are used as fillers. Cellulose, glass fibres, wood veneers or small mica plates are also used, and these fillers may have four or five times the specific strength of metals. Thus the impregnating plastic is encouraged to much greater strength, and the material is provided with a greater resistance to shock.

As Fig. 1 shows, the percentage weight of plastic in the laminated plastic must be carefully controlled to be a minimum, consistent with satisfactory bonding of the filling fibres[1]. The properties of the laminated plastic will also depend on the orientation of the filler fibres. For example a material with all its fibres aligned in the same direction will have good tensile and compressive properties in the direction of the fibres, but would be poor in tension and compression in other directions, and would have poor shear properties. This drives home the point that highly specialised materials, of greater specific strength than metal, can be made up to meet the most stringent requirements. There is nothing revolutionary about this process of building up a stress-carrying material. Plywood is another similar device using synthetic bending plastics to obtain strength.

As may be imagined, due to the varying methods of preparation and of test, the mechanical properties of plastics will vary widely. Table I is intended to give only an indication of the strengths obtainable.

3. PROPERTIES OF LAMINATED PLASTICS

The properties of laminated plastics are listed, and as a basis for assessment, a close comparison is made with conventional metal construction.

3.1. Aerodynamic properties

The actual surface finish obtainable on laminated plastics is better than with metals. The surface is continuous and clean, not being disturbed by rivets, skin joints, and so on. Also the thicker plastic skins will retain their shape, and will not develop bumps or depressions, which can be formed readily in metal skins. All these points tend to provide more favourable conditions for laminar flow.

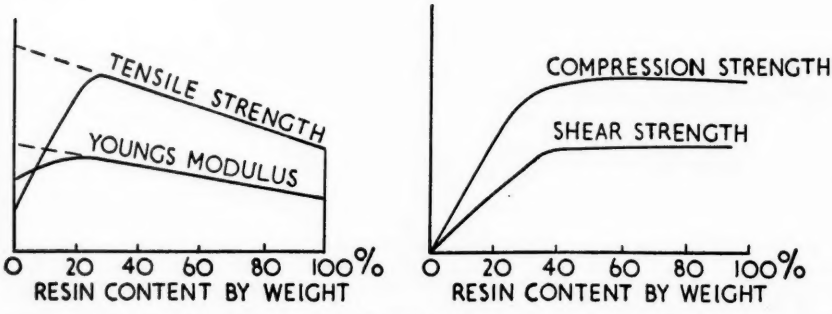

Fig. 1. Variation of mechanical properties with resin content for typical plastic.

3.2. SERVICEABILITY

3.2.1. *Moisture*

The majority of plastics tend to gain or lose moisture as the relative humidity varies, and this is particularly marked where cellulose reinforcement is employed. Dimensions, weight, and mechanical strength are thus affected by this. For example, paper-based phenol formaldehyde shows a loss in strength of 18 per cent. at 75 per cent. humidity after 20 days, and 40 per cent. loss in strength at 100 per cent. humidity after a similar time. After 20 days exposure, the strength of the plastic does not drop further[1].

Methods of combatting this have yet to be reported, but the prevention, by suitable selection of resin, would appear to be easier than the cure. Generally, an increase in curing pressure or temperature reduces the effect.

It should be pointed out that many plastics —notably asbestos-based—do not suffer any ill effect from moisture.

3.2.2. *Temperature*

Recent research[6] in the United States has indicated that aircraft materials should generally retain their mechanical strengths over a temperature range from $-60°$ C. to 150° C. The lower limit is set by reason of wind chill on cold surfaces, and the upper by aerodynamic heating. The effect of temperature acts principally on the resins, and is less severe on those where the fillers are unaffected by temperature. Suitable laminated plastics exist at the present day up to about 130° C. and down to below $-60°$ C.[1] Durestos, an asbestos-based laminate, is rather better than most in its reaction, increasing 5 per cent. in strength at $-60°$ C. and decreasing 15 per cent. at 100° C. Fibre glass and paper-based laminates are more indicative of the general trend, increasing 10 per cent. at $-60°$ C. and decreasing up to 40 per cent. at 100° C. High grade aluminium alloys suffer similar temperature changes in strength.

Some plastics tend to become brittle at low temperatures, and research along this line is being done. Investigation is also being made in an attempt to increase the resistance of plastics to high temperatures for use in gas ducts, exhausts, and so on. A limiting defect in plastics, which only appears in special circumstances, is the high coefficient of expansion, which is six to ten times that of metals. This difficulty is usually avoided by special methods of fixing.

3.2.3. *Corrosion and erosion*

Most plastics are resistant to corrosion by the dilute acids, alkalis, and salts that attack metals. Rain erosion of low pressure laminated fibre glass in flight has also been investigated[6]. This showed that there was a high rate of erosion on all surfaces at more than 60° inclination to the rain drops, depending on the sixth power of the speed of the aircraft. Surfaces of less inclination than 15° showed little or no erosion. To

TABLE I

STRENGTHS OF SOME LAMINATED PLASTICS AND METALS

	Specific gravity	*Tensile strength* (*lb./in.*^{2})	*Compressive strength* (*lb./in.*^{2})	*Shear strength* (*lb./in.*^{2})	*E* (*lb./in.*^{2} $\times 10^{-6}$)	*Specific* *Tensile stress* (*lb./in.*^{2})	*Specific* *E* (*lb./in.*^{2} $\times 10^{-6}$)
"Durestos" (asbestos)	1.27	15,250	13,000	5,000	2.0	12,000	1.57
"Aerolite" (flax)	1.43	70,000	34,000	2,000	2.0	49,000	1.4
Resinated plywood	0.70	15,300	10,500	4,500	1.5	21,900	2.14
Fibre glass (polyester)	1.82	43,000	42,000	8,000	3.0	23,600	1.65
Duralumin	2.8	60,000	60,000	36,000	10.0	21,400	3.57
Steel	7.8	112,000 to 200,000	112,000 to 200,000	80,000 to 112,000	28.0	14,400 to 25,600	3.59

indicate the severity of the effect, at 400 m.p.h. large raindrops could cause serious damage to an aircraft in a few minutes. Leading edge erosion is critical, and adequate protection has been found in the application of 1/100 inch thickness of neoprene, which does not impair the electrical or mechanical properties of the laminate.

3.3. Dielectrics

As almost all plastics are non-conductors, most aerial installations can be built into the aircraft. This principle could have wide application to all types of electrical fittings. This same property, applied to heat, offers a good insulation of the cabin from aerodynamic heating, which may become serious at high speeds.

3.4. Structural properties

3.4.1. *Ties*

Laminated plastics possess good properties for ties subjected to pure tension. The factor of merit is the specific tensile strength and, in this, several laminates exceed duralumin by about 60 per cent. However, due to the poor shear properties, large end fittings must be used.

3.4.2. *Struts*

When design of a strut is limited by instability, the factor of merit of the material varies as EI. This, for rigidity in one particular direction, is proportional to E/ρ^3. Where the nature of the strut is such that it may collapse in any direction, the factor of merit is E/ρ^2 (*see* Appendix, Section 4). It can be seen from Table I that plastic struts compare favourably with metal ones. When the design is not limited by instability, the specific compressive strength is the factor of merit and, again, there are plastics more efficient than metal.

3.4.3. *Gluing*

Because of the lower stresses existing in plastics, gluing and bonding may be used to the exclusion of riveting. In wood gluing, the strength of a joint is thought to depend, firstly, on a mechanical anchoring of the glue within the pores of the wood, and secondly, on the adhesion between the glue and the wood. A depth effect in laminated plastics is excluded because of the dense structure of the material. Hence, the adhesive force between the glue and the material is decisive. In 1940 research with "Kaurite" cold-setting glue "enables us to consider the problem of gluing laminated plastics as solved."[4] Since then, further improvement and development of cold-setting glues has been made.

Because of the poor bearing properties of plastics, it is not generally advisable to bolt or rivet plastic joints. It was found in bearing tests at the Bristol Aeroplane Company that bolted joints tend to slip at small loads, and this effectively fails the joint.

3.4.4. *Fatigue and creep*

Fatigue levels are generally good. Resistance to fatigue, based on allowable stresses, is claimed to be 50 per cent. higher than that for a heat-treated aluminium alloy. This resistance is thought to be influenced by the temperature and pressure of moulding.

The creep characteristics are not as favourable. On a test piece of "Aerolite," a creep limit of 75 per cent. of the instantaneous static strength was found over a period of 500 hours[5].

3.4.5. *Flutter*

In current designs, the two most prominent factors influencing the flutter speed are the torsional and flexural stiffnesses. These are directly proportional to the operative shear and Young's moduli and, from Table I, the specific moduli are seen to be much lower for plastics than for aluminium or steel. Thus for wings of similar design, in general flutter speeds will tend to be lower with plastics, but a mitigating factor is the greatly increased structural damping provided by all plastics, the energy absorption being 20 or 30 times that of metals.

4. Sandwich Construction

Sandwich construction is one of the essential ingredients of the plastic aircraft, and it is directly comparable to the skin-stringer combinations of the stressed skin construction. In its elements, it consists of two skins

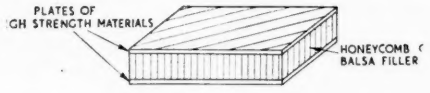

Fig. 2.

separated by a low density medium known as the filling (Fig. 2). For forces in the plane of the sandwich, it acts as an ordinary plate, the

filling sustaining some of the forces, or not, depending on the type of filling; but, for normal forces, it possesses the advantage of great flexural rigidity. The plates may be of any high strength material, metal or laminated plastics; only the plastics are considered here. The object of the fillers is primarily to retain the skins in their correct relative positions, to transmit normal forces between them, and to prevent them "crinkling" locally. They must also be light, and easily attachable to the plates.

4.1. TYPES OF FILLING

4.1.1. *Continuous*

(*i*) *Balsa wood*: Balsa has all the inherent difficulties associated with wooden construction, namely wood control and complications of shaping. It has poor resistance to moisture decay, fungus, and fire. Nevertheless, it is suitable for sandwich construction because of its good structural properties, and because it is easy to bond to the plates.

(*ii*) *Expanded and Foamed Plastics*: Foamed materials have been developed intensively in the United States with the object of making possible direct injection of the foam between the pre-moulded plates. Several problems, however, are still unsolved in this attractive proposition, such as poor temperature characteristics, and distortion of the foam bubbles, which contribute to a large reduction in strength of the filler. At present, "there are no satisfactory resinous materials found for use with laminates in sandwich construction."[4]

4.1.2. *Discontinuous*

Grids of wooden or metal stringers; spacers; corrugated sheets; honeycombs: Of these, it has been found that the honeycomb filler is most suitable as a filler. It is very light, permits high operating stresses, although carrying no end load itself, and has a good resistance against fatigue, creep, moisture, decay, fungus and fire. A technique has now been developed whereby the honeycomb can be moulded between two layers of laminated plastic, so as to form a sandwich in one operation. This removes the rather critical problem of satisfactory adhesion between filler and plate.

4.2. TYPES OF INSTABILITY

There are three main types of instability. The first, and usually the most serious, is the overall Euler buckling with both skins moving sympathetically. Secondly, there is the buckling of the face sheets into the honeycomb cells. And, lastly, the "crinkling" or waving of a face, supported elastically on the filling. This occurs in quite small wave lengths, and the buckling of one face occurs independently of the other.

TABLE II

Type of filler	*Density* ($lb./ft.^3$)	E ($lb./in.^2$)	G ($lb./in.^2$)
Balsa	6	350,000	15,000
Typical expanded foam	6	6,000	5,000
Paper honeycomb	1.8	20,000	10,000

Many treatments of these instability phenomena have been made[8], some of which include the effect of eccentricities, and good experimental agreement is found.

4.3. DESIGN OF A SANDWICH PANEL

As an illustration of the design problems, consider the design of a sandwich panel to carry a compressive load P lb. per unit length over a pin-ended length l. Apart from the actual geometry of the sandwich, there is a choice of the types of materials to be used. This is assumed to have been investigated, and the best materials selected. Thus, if h is the thickness of the sandwich and t the thickness of each plate, the parameters P/l, h/t and h/l must be considered.

For the most efficient operation of the sandwich, the maximum operating stress must coincide with the lowest instability stress. By suitable adjustment of the core, the local buckling instabilities are not critical. As a buckled panel is a failed panel, so the possibility of shear buckling must be investigated, and this is found not to be critical on conventional aircraft. The justification of this, and the various instability stresses are listed in the Appendix. The tension between the filler and the plate has also been calculated, and is well within the range of present day glues.

Having defined the materials, the instability equations determine a maximum limit on l/h and a minimum limit on t/h for a given value of P/l. It is too much to hope that the structure thus defined is the one of minimum weight, and thus the only way to achieve a more efficient construction, is to use materials of greater strengths. At

present this is not possible and efficiencies of about 20 per cent. below that achieved with skin stringer combinations, are obtained. However, the discrepancy between the materials is not quite as large as 20 per cent., as no account has been taken of the transverse stiffness of the sandwich, with its fewer ribs and frames, thus saving weight.

The advantages to be derived from the sandwich are greatest where a component has to carry a low compressive load over a great length. And it is least efficient where high compressive loads have to be carried over short lengths, and there is little risk of buckling.

5. DESIGN AND CONSTRUCTION OF AN AIRCRAFT

Simplicity, which is the backbone of efficient production methods, is a fundamental of plastic design. The possibility must be considered of replacing a mass of small component parts by a simpler structure of equivalent properties, with possibly a consequent loss in structural efficiency. Plastics are suited to this type of construction. It is not suggested at present that the entire air frame can be built of laminated plastics, but there seems no reason to suppose that at a later date even this might not be achieved.

As efficient metal and plastic designs are so fundamentally different, one of the biggest problems would be that of converting the main body of a design team—draughtsmen and designers—to *think* in terms of plastics rather than metals.

5.1. FUSELAGE

The construction of a fuselage may be foreseen in two ways:—

(*i*) *Panel construction*, as used on the Bristol Type 175. This is not so easily applicable to plastics as to metals, because of the difficulty of final assembly. The possibility of riveting up the panels makes it attractive in metals, but gluing problems in plastics would be difficult.

(*ii*) *Sectional or complete assembly*. This method would appear to be more suited to plastic construction than (*i*). For small aircraft, the fuselage can be assembled at once, complete; but with large aircraft, a sectional method would be more suitable, in order to keep the size of the assembly to reasonable limits. The final assembly of these sections presents no great difficulty as both skins of the sandwich are readily accessible for gluing.

The gluing processes involved can be divided into two categories, the assembly of the main structural members, and the production of sub-assemblies. In the main assembly, recesses in the mould could accommodate the internally-fitted parts, such as frames. These are dressed down to the level of the contours of the mould, and the sandwich construction started. It may be advantageous to part-cure the inner skin before finally assembling the outer skin. The temperature curing of the whole structure can now be done, either by vacuum or pressure moulding. In the first of these processes, the air surrounding the material is removed through rubber blankets and a vacuum pump, atmospheric pressure being exerted on the material. In the second, the pressure can be obtained by some clamping or air bag device.

Having dealt with construction, the design of a fuselage is now considered.

5.1.1. *Skins*

Because of the low Young's modulus, stringer skin construction is not very suitable in laminated plastics, but sandwich construction is able to employ a material of lower modulus, and still produce an efficient structure. It is also particularly suited to curved sections, since its inherent stability permits the elimination of a large part of the internal stiffening structure—stringers, bulkheads, and so on.

Pressurisation hoop stresses are carried by both of the sandwich skins, and it may be shown (*see* Appendix) that the strengths of the fuselage in various directions are well suited to the required design strengths. A circular fuselage, slightly thickened at the bottom, has a reverse loading of about 65 per cent., and a sideways bending of about 75 per cent. of the vertical bending strength. This generally approximates to the required bending strength of a fuselage.

5.1.2. *Frames*

Because of the stiffness of the sandwich skin, the redistribution of shear usually performed by frames is not needed, and so the purposes of a frame are to provide an attachment between floor and fuselage, and to support the sandwich construction. Thus it would seem that the frames will not be

dissimilar in shape and spacing to those of metal construction. Because of the poor shear properties, attachment of the transverse floor beams is a problem necessitating bulky fittings. However, it may be possible to insert some local reinforcement in the shape of a high shear plastic, a wire mesh, or even Redux bonded alloy double plates. Generally, however, metal to plastic joints are not a sound proposition.

5.1.3. *Cut-outs*

The problem of shear redistribution at cut-outs is not as serious in sandwich construction because of the stiffer skins. Longerons and stub frames placed between the skins of the sandwich can deal with the diffusion of end load and hoop stresses, and will be more efficient than their metal counterparts, because of their higher specific strengths. A sub-assembly of longerons, stub frames and window frame moulded into one structure would appear to be attractive. This could then be inserted, whole, into the final assembly.

5.1.4. *Floor*

Plastic floors have been found to be fairly satisfactory, and with the knowledge gathered from the increased use of plastics, a sandwich construction can be visualised using Balsa as the filler because of its greater crushing strength. Longitudinal booms beneath the seat attachments, to take out their moments, would seem to be well suited to this type of construction. Local attachments can be dealt with as in Section 5.1.2.

5.2. WING-FUSELAGE JOINT

A more detailed investigation would be needed for this, but due to greater efficiency of the sandwich in diffusion of end load, the difficulties would seem to be more readily overcome. Also, plastic longerons are more efficient, and reinforcement is obtained by simply increasing the skin thicknesses.

5.3. WINGS

The design, manufacture, and testing of plastic wings are admirably described in a series of reports from the Royal Aircraft Establishment[3]. Thus it is proposed to give here only a brief description of the method and results, and to quote the final sentence: "We hope to be able to show that the weight saving and other advantages which could be realised by plastic structures, will be so large, as to offset the admittedly very great difficulties of adopting them."

"Durestos" has satisfactory shear properties, but lacks in direct strength. To reinforce this, thin strips of "Aerolite" of high specific direct strength were inserted in the "Durestos" felts. Their combined properties provide a material suitable for wing construction.

The wing skin consists of this thick "Durestos"–"Aerolite" sheet, and is supported by a paper honeycomb that fills the entire inside of the wing. Sandwich construction is not used and the need for ribs is thus removed. The entire wing from leading edge to rear spar is cured in one piece on a concrete mould made to the desired internal shape. The process is a vacuum temperature moulding with the heat supplied by electrical strip heaters. After removal of the mould, the honeycomb material is inserted and cured under a pressure process. The wing is then complete.

The wings thus moulded were found to be about 15 per cent. stronger and stiffer than metal wings of the same weight. It should be pointed out that these figures were derived in comparison with a wartime aircraft—the Spiteful.

The authors of the Report conclude that

(*a*) The mechanical properties of low pressure moulded "Durestos" under vacuum conditions are in no way inferior to those of "Durestos" moulded at high pressure.

(*b*) It is practicable to mould plastic components of unlimited size and containing numerous inserts.

6. DEVELOPMENT OF LAMINATED PLASTICS

An interesting method of assessing the efficiency of a structural plastic has been evolved in Ref. 2. The weight of a structure is determined by the product of two quantities, the efficiency of the material in resisting loads, and the efficiency of the structure as a structure. The first can be assessed mathematically as the product of three further quantities—the specific fibre strength, that fraction of the strength of the fibre that is actually used, and the efficiency with which the fibres are orientated for a desired property. The second, namely the efficiency of the structure as a structure, is more difficult to assess and includes all the empirical qualities grouped under the term "good design."

On this basis, it can be shown that with more control over the fibre orientation, the efficiency of the laminated plastics being used can be greatly increased. This approach also permits the theoretical assessment of various laminated plastics, and indicates the path of the most fruitful research.

As an indication of the improvements foreseen, a plastic, with mica as the filler, should possess an efficiency of five times that of the present day laminates. Theoretically, at least, this points to an aircraft about five times as light as the conventional aircraft of today, although the cost would be considerable.

7. CONCLUSIONS

It is only when mass production is contemplated that the most conspicuous advantages to be obtained can be translated into real gain. Thus, as the number made of any one particular type of civil aircraft is usually limited, it is doubtful if plastics would be seen to their best advantage in this application. Their potentialities lie rather in the manufacture of large numbers of identical aircraft, where quantity production is of prime importance. Their application to military aircraft of all sizes is thus reasonable.

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APPENDIX

1. *Summary of principal plastic properties compared with those of metal and wood*

	Wood	*Metal*
Advantages of Laminated Plastics	More permanent and easily worked	Easily worked
	Not as weak in shear, parallel to grain, so joints not so bulky	Less vibration trouble
	Not as weak in stiffness perpendicular to grain	Instability problems reduced
	Not so variable control, and liable to defects, *e.g.* knotting	Stiffer
Disadvantages of Laminated Plastics	Temperature processing More expensive	Less strong

2. *Summary of instability stress in sandwich construction and other data.*

(*a*) Euler instability stress $f_{crit} = \dfrac{(\pi^2 E/4)(h/l)^2}{[1+(\pi^2/3)(E/\mu_{31})(t/h)(h/l)^2]}$ [Ref. 8]

(*b*) Shear buckling stress $\tau_{crit} = \dfrac{5.35\,\pi^2 E h^2}{4(1-\nu^2)b^2}$ [Ref. 8]

(*c*) "Crinkling" stress $f_{crit} = 0.6 E_1^{\frac{1}{3}} E_3^{\frac{1}{3}} E^{\frac{1}{3}}$ [Due to Cox]

(*d*) Panel weight per unit width $W = 2t\rho l + h\rho_F l$.

To assess whether these stresses are critical, a comparison is made with a large aircraft for which

(*i*) the fuselage radius is 70 in.

(*ii*) the ultimate fuselage design shear force is 100×10^3 lb.

(*iii*) the ultimate fuselage design bending moment is 40×10^6 lb. in.

(*a*) To establish some order of magnitude of the geometry of the sandwich.

Now
$$f_{crit} = \frac{(\pi^2 E/4)(h/l)^2}{1+(\pi^2/3)(E/\mu_{31})(t/h)(h/l)^2}$$

i.e.
$$\left[1+\frac{\pi^2}{3}\frac{2\times10^6}{10^4}\left(\frac{t}{h}\right)\left(\frac{h}{l}\right)^2\right] f_{crit} = \frac{\pi^2}{4}2\times10^6\left(\frac{h}{l}\right)^2 \quad . \quad . \quad (1)$$

And
$$P/l = 2(t/h)(h/l)f_{crit} \quad . \quad . \quad . \quad . \quad (2)$$

So Table I may be constructed from (1), establishing various values of f_{crit} for values of h/l and t/h.

TABLE I

TABLE OF f_{crit}

	$l/h=$ 10	20	30	40
$t/h=0.02$	44,100	12,100	5,470	3,100
0.04	39,400	11,700	5,400	3,080
0.05	37,600	11,500	5,370	3,070
0.10	30,000	10,500	5,220	3,020

So for $f_{crit}=13{,}000$ lb./in.^{2} and $P/l=100$, Table I and equation (2) give $l/h=18$ and $t/h=0.06$, and for $f_{crit}=13{,}000$ lb./in.^{2} and $P/l=150$, similarly $l/h=18$ and $t/h=0.09$.

For the example aircraft $P=M/(\pi R^2)=40\times10^6/(70^2\times\pi)$, and therefore for $l=20$ in., $P/l=150$.

Hence the approximate dimensions of the sandwich are $h=1$ in., $t=1/10$ in.

From (*d*) $W=2t\rho l+h\rho_F l$

$$=\frac{\rho l^2(P/l)}{f_{crit}}\left[1+\tfrac{1}{2}\frac{\rho_F}{\rho}\frac{h}{t}\right], \text{ where } P=2tf_{crit}.$$

So for minimum weight $\frac{1}{f_{crit}}\left[1+\frac{1}{2}\frac{1.8}{170}\frac{h}{t}\right]$ must be a minimum (using $\rho_F=1.8$),

i.e. $\frac{1}{f_{crit}}\left[1+\frac{1}{200}\frac{h}{t}\right]$ must be a minimum.

However the values $f_{crit}=13{,}000$ lb./in.^{2} and $P/l=150$ can be shown to be not near a minimum.

(*b*) *Shear buckling*
$$\tau_{crit}=\frac{5.35\times\pi^2\times2\times10^6\times1.0}{2\times0.9\times b^2} \quad . \quad . \quad . \quad . \quad (3)$$

from Ref. 3.

For the example aircraft τ is a maximum at the centre line and is equal to (shear)/(πRt).

So $\tau=10^5/(\pi\times70\times2t)$ and $t=0.1$, *i.e.* $\tau\simeq10^4/4.4$ lb./in.^{2}

Now $\tau_{crit}\simeq10^8/b^2$ lb./in.^{2} from (3).

So if $b^2 < 4.4 \times 10^4$, *i.e.* $b < 2.1 \times 10^2$, shear buckling will not occur, and as b will be considerably less than this it may be ignored.

(*c*) *"Crinkling"* $f_{crit} = 0.6 E_1^{\frac{1}{3}} E_3^{\frac{1}{3}} E^{\frac{1}{2}}$

$= 0.6 (2 \times 10^6)^{\frac{1}{2}} (2 \times 10^4)^{\frac{1}{3}} (500)^{\frac{1}{6}}$

$\simeq 50{,}000$ lb./in.^{2}

According to Howard, it will be difficult to achieve 90 per cent. of this value. So the probable $f_{crit} \simeq 50{,}000$ lb./in.^{2}

The operating compressive stress = 13,000 lb./in.^{2}, and so "crinkling" is not critical.

3. *To find optimum Reverse and Sideways Bending Strengths in relation to Vertical Bending Strength*

For "Durestos," $f_{compressive} = 13{,}000$ lb./in.^{2}; $f_{tensile} = 15{,}250$ lb./in.^{2} and $E = 2 \times 10^6$.

Let R, the radius of fuselage be 70 in. The neutral axis must lie below the centre line for the most efficient vertical bending strength, giving ultimate stresses to tension and compression sides, *i.e.* at (1.125/28.25) R below the centre line. This may be achieved by a local thickening of the skins at the bottom. So reverse bending will be $(13/15.25)^2 \times M_{vert} = 0.65\ M_{vert}$ (approx.), and sideways bending will be about 0.75 M_{vert} (approx.).

4. *Derivation of Factors of Merit for Struts*

Consider (*a*) the strut that may fail in any direction—namely a square section of side a and (*b*) a strut that may fail in only one direction—namely a thin rectangular section of width a' and length wa'.

Then we have,	*For* (*a*)	*For* (*b*)
W = Weight/unit length	ρa^2	$\rho w a'^2$
Moment of inertia	$a^4/12$	$w^3 a'^4/12$
Factor of merit (EI)	$Ea^4/12 = EW^2/(12\rho^2)$ $\propto E/\rho^2$	$Ew^3 a'^4/12 = EW^3/(12 a' \rho^3)$ $\propto E/\rho^3$ (as a' is determined by other considerations)

REVIEWS

The following are reviewed:—

Mathematical Engineering Analysis
Dimensional Analysis and Theory of Models
Carburation (Applied Carburation and Petrol Injection), Volume I.
Combustion, Flames and Explosions of Gases
Introduction to the Study of Aircraft Vibration and Flutter

MATHEMATICAL ENGINEERING ANALYSIS. R. Oldenburger. The Macmillan Company, New York, 1950. 426 pp. with examples and index. 45s. net.

The aim of this book is to enable the reader to express the physical relations between the members of a given experimental system in mathematical terms. The basic laws of engineering systems are developed from the minimum number of assumptions and various simplifications in treating these systems are discussed. The book assumes a knowledge of the higher calculus, including line, surface and volume integrals, Green's theorem and Stokes' theorem. Thus it should be of greatest use to the pure mathematician in need of an introduction to the field of applied mathematics as used by the engineering industry.

Part I deals with the mechanics of rigid bodies with examples of systems with springs and damping. Simple applications are given of gas turbine-driving generators and of diesel engines driving marine propellers. There is a brief treatment of dimensional analysis.

Part II deals with electricity and magnetism, starting from definitions of magnetic force and potential, forces on conductors, Faraday's law of induction, and Kirchhoff's laws. There is a chapter on simple electrical networks, impedances and the mathematical formulation of a linear network, and examples are given of the equations governing D.C. motors and generators, filters, neon tubes and rectifiers. Another chapter gives Maxwell's equations for electromagnetic flow.

Part III deals with heat, giving definitions of heat, internal energy, work and enthalpy, and adiabatic, isothermal and isobaric processes. Applications are given of gas flow through convergent nozzles and flow into a vessel, and the thermodynamic processes of a gas turbine are treated briefly. There is a chapter on the second law of thermodynamics and another on heat transfer, with applications to turbine blades.

Part IV deals with the fundamental theory of elasticity, determining the stress-strain relations. Examples are given of elastic systems in one, two and three dimensions with applications to loaded beams, rectangular plates, torsion of circular shafts, and membranes.

Part V deals with fluid mechanics, establishing the equations of continuity and of motion, and dealing briefly with viscous fluids, compressible liquids and gases. There is a short chapter on elementary aerodynamics.

There are a number of exercises.

Covering such a wide field, the treatment in each part of the book is mainly introductory. It must be emphasised that the book will be of use primarily to those readers with a good background in pure mathematics.

DIMENSIONAL ANALYSIS AND THEORY OF MODELS. Professor L. Langhaar. John Wiley & Sons Inc., New York. 4 dollars. Chapman & Hall Ltd., London, 1951. 166 pp., 15 figures. 32s. net.

This book goes into its subject more thoroughly than is customary in aeronautical education in this country. Preliminary considerations leading to a statement of Buckingham's theorem are followed by a valuable Chapter 3 on the systematic calculation of dimensionless products. Many engineers will doubtless remain content with Rayleigh's approach with its infinite series, though the assumption involved be unnecessary to dimensional analysis, but

Chapter 3 provides means to check the number of non-dimensional products when doubt arises, and this step is not brought out clearly in many summary treatments that exist. Rules of procedure might perhaps have been collected together more conveniently. Chapter 4, on the algebraic theory, can be passed over with little loss by engineers. Of the remaining six chapters five are devoted to applications covering an exceptionally wide range; including, for example, under-water explosions, riveted joints, airport pavements, watersheds, and problems of heat transfer and electromagnetism besides fluid mechanics. Some are ingenious and many stimulating. In addition, problems for exercise are appended to each chapter.

Dimensional analysis has grown up with aeronautics and now makes a wide appeal, which Professor Langhaar's account should go far to satisfy. The senior engineer, confronted with problems ranging over several different branches of his profession, is thankful for all such principles which exert a unifying influence. Whether the harassed student can find time for all the attention the subject deserves is perhaps questionable.

CARBURATION (APPLIED CARBURATION AND PETROL INJECTION), Volume I. Charles H. Fisher. Chapman & Hall, London, 1951. 356 pp. Illustrated. Index. 36s. net.

This publication is the first of two volumes of a revised Third Edition, and deals with the theoretical and practical aspects of carburation as applied to engines in general, and to automobile and aircraft engines in particular.

The primary duties of a carburation system are concerned with metering fuel accurately in accordance with engine requirements and ensuring that the fuel is delivered in a state best suited to the combustion process. Since these activities are closely linked with other contributory factors such as induction manifold layout, fuel characteristics, and operating conditions, it is not surprising that considerable attention is focused on these items throughout the book.

The introductory chapter represents a brief survey of the subject as a whole and introduces the principal factors having a bearing on the overall performance of the system. At the end of the chapter, the various requirements to be satisfied by the modern automobile carburettor are listed and discussed in detail. Chapter 2 is allocated to fuels and describes at some length the many properties associated with the vaporising and combustion processes. The following chapter is largely concerned with the fuel/air mixture characteristics and their influence on thermal efficiency and engine performance.

Chapters 4 and 5 give detailed descriptions of the numerous devices incorporated in different types of carburettor and explain how they operate. The elementary metering laws governing the flow of fuel and air through the carburettor are also developed with the aid of simple formulæ. Chapters 6 and 7 study the influence of the induction manifold design on the general performance and outline means for assessing mixture distribution with reasonable accuracy. Chapter 8, covering 100 pages, is the section devoted to aircraft carburation and petrol injection. It gives an account of several systems in service both in this country and abroad and also provides much information regarding petrol injection equipment used by the Germans during the Second World War

There is a pronounced American flavour about the book, no doubt due to the frequent references to American reports. While it must be admitted that the examples employed admirably illustrate and reinforce the points made by the author, one wonders why more use has not been made of material nearer to hand.

Although the different aircraft injection systems are described functionally, a feature that might easily escape the readers' notice is that, where most British types are concerned, there is a marked absence of air-measuring elements and suchlike obstructions in the induction tract. This renders them less liable to impact icing troubles and permits better breathing at full throttle. In view of the metering problems associated with "boost reversal," which is a condition experienced at low r.p.m. in engines employing large valve overlaps, it is surprising that it gets no mention.

The references to pressure in such terms as "partial vacuum," "negative pressure" and "high depression" appear at times to be unnecessarily confusing when in most cases all that is meant is "reduced pressure." The "pressure drops" given on p. 204 in inches of mercury absolute do not help matters.

On the whole the book is well produced and the contents liberally illustrated and lucidly explained. It contains a wealth of information and can be strongly recommended to those interested in the subject.

COMBUSTION, FLAMES AND EXPLOSIONS OF GASES. Bernard Lewis and G. Von Elbe. Academic Press Inc., New York, 1951. 795 pp., 355 figures. Appendix. 96s. 6d. net.

This book, although having the same title as the 1938 edition, is an entirely new text, in which the whole subject matter is brought up to date. It is divided into four parts.

Part I describes the chemistry and kinetics of the reactions of fuel gases with oxygen, and in detail with hydrogen, carbon monoxide and various hydrocarbon gases. The theoretical foundations of chain reactions are well set out in an initial chapter and the authors have not been shy of using mathematics to give precision to the subject. The hydrocarbon chapter ends with an account of recent work on engine knock.

Part II on Flame Propagation is the largest section and Chapter VII is an immense compendium of knowledge on combustion waves in pre-mixed gas mixtures under laminar flow conditions. There is a wealth of graphical test data which should be a joy to the specialist. By comparison the chapter on flames in turbulent streams is nothing like so generous as the combustion engineer might wish. Unmixed fuel jets for both cases are also treated in a separate chapter.

The chapter on the theory of the detonation wave, although standard in treatment, is marred by failure of the authors to make clear the difference between the general solution and the particular solution of Chapman-Jouguet. The reader is led to believe that there is some fundamental difference between ordinary shock waves and detonation waves. In fact one is only a more general case of the other. The authors' attitude to this problem has led them completely astray in some cases. On page 600 it is stated that a piston moving with the particle velocity of the gas following a detonation wave does no mechanical work on the system. This is quite untrue; the piston must do mechanical work under the conditions stated. At the end of the same paragraph it is stated: "It is obvious that if the piston were allowed to follow the wave at a velocity w (the particle velocity), no steady state would be attained and the wave would accelerate." This is untrue; there is a steady state solution to this problem whether heat is released or not. In spite of these defects this is an interesting chapter which contains information on the phenomena of spin and periodic change of velocity in detonation waves. One would have thought that the rather remarkable experiments of Bone, Frazer and Wheeler on the behaviour of detonation waves when passing through an electric field were worth a mention in the chapter on detonation. A reference to their papers is given in a chapter on flames in electric fields, but no indication of the subject matter.

Part III is a shorter section dealing with conditions in the burnt gases, the analysis of band spectra, dissociation in terms of measured temperature and pressure, thermal radiation and so on.

Part IV, Technical Combustion Problems, consists of forty pages which are so sketchy and elementary as to be quite unworthy of a place in such a book. Only three pages are devoted to industrial heating and pressures which would use directly the work described in the book, while twenty pages are used up in elementary discussion of engine cycles, surely available elsewhere.

Apart from Part IV the reader can be well recommended to this masterly book on combustion, with the proviso that the title is taken literally. It deals with the combustion of gases only and does not touch the problem so important in the gas turbine—the combustion of a fuel spray. The authors do not appear to be aware of this; but how much better the work would be if Part IV could be replaced by a section dealing with the evaporation and combustion of liquid fuel sprays, along the line of the work of Spalding at Cambridge, for instance.

The book is well set out and printed, with a host of diagrams and a useful Appendix of thermo-chemical data.

INTRODUCTION TO THE STUDY OF AIRCRAFT VIBRATION AND FLUTTER. Robert H. Scanlan and Robert Rosenbaum. Macmillan & Co., London, 1951. 428 pp. Illustrated. Index. 56s. net.

In writing this book the authors have undertaken what is essentially a pioneering effort. Flutter is a complex and still expanding subject and the scientific literature on it is immense, but apart from some slight treatment given to it by Freberg and Kemler* it has not yet

* "Aircraft Vibration and Flutter," C. R. Freberg and E. N. Kemler (1944).

been broached in textbooks. Apart from anything else, therefore, the authors of this present book must be given credit for breaking ground which has remained too long unbroken.

The book falls into three fairly distinct sections. The first seven chapters contain a selection of basic material, already available in the standard textbooks, relevant to vibrations and the more mechanical aspects of flutter. They cover mathematical techniques, Lagrangian equation analysis, single- and two-degree-of-freedom systems, basic beam structural relationships, and uncoupled beam vibrations.

The next six chapters are concerned directly with the flutter problem, beginning with the derivation of the flutter equations for a two-dimensional wing/aileron type of flutter based on the Lagrangian approach using uncoupled modes, and proceeding thence to the inclusion of three-dimensional aspects and the use of normal (coupled) modes. A brief survey of several types of tail flutter is also given and some mention is made of empirical methods of flutter prevention, mainly mass-balancing. This section concludes with a chapter on methods of solving the flutter equation.

The remaining three chapters of the book deal with divergence and aileron reversal, instrumentation and testing, and vibration and flutter of swept-back wings.

Throughout the main text the aerodynamic side of the flutter problem is largely set aside, but an Appendix gives some account of unsteady flow aerodynamic theory together with the detailed derivation (following Theodorsen) of the aerodynamic flutter derivatives for two-dimensional incompressible flow.

In its general layout the book is eminently readable. It contains a number of errors (mostly in suffix notation) which will no doubt be corrected later, and the Index could be more detailed. Although the fairly comprehensive bibliography contains many references to British work the book is essentially an exposition of American thought and practice, which in some respects differs from the British. For example, little is said about either tab flutter or the effect of body freedoms—two matters which have received much attention in this country. There is also relatively little concern with design criteria for flutter prevention. On the other hand, interesting methods are given for the calculation of vibration modes and for the solution of the flutter equation.

A general criticism of the book could be that the subject is given an uneven treatment, some portions being considered in much detail, others rather scantily. It is concerned more with fundamental methods than with factual information and will probably be of more value to the student than to the practising engineer or research worker. As an introduction to the subject, which is all that the authors claim for it, and as a very usable reference for analytical methods, this book can be recommended to students and engineers alike.

INTERNAL COMBUSTION ENGINES. Lester C. Lichty. McGraw Hill Book Co. 598 pp., 461 figures. Sixth Edition 1951. 59s. 6d. net.

After a decade of intense industrial progress an up-to-date edition of this famous book is very welcome. Since the 1939 edition, and under the stimulus of war, we have seen the advent of the turbo-jet, turbo-prop, composite engine, ram jet and rocket into service; all of these exemplify new forms of the internal combustion principle. Although these newcomers take up so much of the present stage of urgency in aeronautics the piston engine remains the most important automotive engine. The engine which wrought the revolution in transportation still remains the most popular and the most virile prime mover in the automotive engineering industry.

Lichty's book has always catered strongly for the aeronautical side. This edition makes a determined attempt to keep abreast of developments by introducing basic material on the gas turbine, ram jet and rocket, but the book is still concerned predominantly with the theory, technology and design of the piston-type engine. It retains the conciseness and clarity of style which characterises the earlier editions. Of all the books on the high-speed internal combustion engine it shows the student how to use the information obtained from reliable automotive engine research by stating the important experimental results in a well-digested form; this is no mean achievement in a wide subject which has seen such advances as in the past few years.

As in previous editions, the text begins with chapters on thermodynamic principles and of deviations from the ideal, from which it leads to the subjects of fuels, fuel metering and combustion. It then opens up into the various avenues of engine performance and design. The treatment is generally suitable for applied mechanical engineering students approaching their final examinations. There are examples and exercises throughout.

New material is provided in many places. Thus, the author has now included accounts of the jet propulsion principle, the rocket motor reaction, exhaust turbo-supercharging, exhaust jet thrust, icing of carburettors, combustion knock, charts for gas turbine processes, to mention a few. The information throughout makes use of the basic results from the relevant original work. Highbrow discussion on the results of unclarified research is avoided.

The engineer will find the common design problems of the high-speed internal combustion engine treated in a modern manner. Professor Lichty is a master of the subject, and from his long service at Yale we can safely conclude that he is also a master of the art of teaching engineering students. His book is highly recommended.

As regards its place in aeronautics, it is almost entirely a piston-engine book. One hopes that the basic technology and theory of the new forms of aircraft propulsion will eventually be written up in the same manner. We shall then have something badly wanted by the rising generation of engineers, a book which will pass on in an equally worthy and dignified form the vital knowledge now being gained in the widening field of aircraft propulsion.

British Standards

The following draft specifications have been received from the British Standards Institution:

CN(ACE)5871—Draft British Standard for high tensile steel unified hexagonal-headed bolts (UNF threads) for aircraft.

CN(ACE)5872—Draft British Standard for high tensile stainless steel unified hexagonal-headed bolts (UNF threads) for aircraft.

CN(ACE)5873—Draft British Standard for aluminium alloy unified hexagonal-headed bolts (UNF threads) for aircraft.

CN(ACE)5874—Draft British Standard for close tolerance unified hexagonal-headed bolts (UNF threads) in high tensile steel for aircraft.

CN(ACE)5875—Draft British Standard for medium tensile steel unified hexagonal nuts (UNF threads) (ordinary, thin, slotted and castle) for aircraft.

CN(ACE)5876—Draft British Standard for high tensile stainless steel unified hexagonal nuts (UNF threads) (ordinary, thin, slotted and castle) for aircraft.

CN(ACE)5877—Draft British Standards for aluminium alloy unified hexagonal nuts (UNF threads) (ordinary and slotted) for aircraft.

CN(ACE)5878—Draft British Standard for unified shear bolts and nuts (UNF threads) for aircraft.

These draft specifications are issued for comment only and comments should reach the Institution by the 26th January 1952. Interested members may borrow the drafts from the Library.

The British Standards Institution announces new Standards for:—

Symbols, Terms and Definitions for Gas Quantities in Reciprocating Internal Combustion Engines (B.S.1798:1951).

Synthetic Resin Phenolic Mouldings for Aircraft (B.S.PLI:1951).

Tab Washers for Aircraft (B.S.SP.41-46:1951).

Turnbarrels, Tension Rods and Swaged Cable-end Connections for Aircraft (B.S.SP.33-39:1951).

ADDITIONS TO THE LIBRARY

The following have been added to the Library (titles of pamphlets are printed in italics; books marked * or ** may not be taken out on loan):—

Anglo-American Council on Productivity. Metal Finishing. 1951.

Baker, J. F. Shortcomings of Structural Analysis. N.E. Coast Engineers and Shipbuilders. 1951.

Birkhoff, G. Hydrodynamics. University of Cincinnati. 1950.

*Bridgman, L. (Editor). Jane's All the World's Aircraft, 1951/2. Sampson Low. 1951.

*British Standards Institution. Glossary of Aeronautical Terms. B.S.185, Part 3. British Standards Institution. 1951.

Butler, E. and G. Young. Marshal Without Glory. Hodder & Stoughton. 1951.

*Cooper, H. J. (Editor). The Royal Aero Club Gazette 1901-1951. Royal Aero Club. 1951.

Department of Scientific and Industrial Research. Mechanical Engineering Research. H.M.S.O. 1951.

Department of Scientific and Industrial Research. Powder Metallurgy. H.M.S.O. 1951.
Gillet, H. W. The Behavior of Engineering Metals. Wiley. 1951.
Heat Transfer and Fluid Mechanics Institute—Preprints. Stanford University. 1951.
Kermode, A. C. Flight Without Formulæ. 2nd edition. Pitman. 1951.
Leeming, J. F. Always Tomorrow. Harrap. 1951.
Lukins, A. H. Modern European Helicopters. G. Ronald, Oxford. 1951.
Mehrens, H. E. Adventures in Aviation Education. American Council on Education. 1951.
Mellor, C. The Airman. John Lane. 1913.
Mises, R. von, and T. von Kármán. Advances in Applied Mechanics. Volume II. Academic Press. 1951.
Morrell, R. S. and H. M. Langton. Synthetic Resins and Allied Plastics. 3rd edition. O.U.P. 1951.
Office of Technical Services. Non-Destructive Testing of Metals. U.S. Department of Commerce. 1951.
Office of Technical Services. Metallising and Joining Ceramics to Metals. U.S. Department of Commerce. 1951.
Reichardt, H. Gesetzmaszigkeiten der freien Turbulenz. V.D.I. 1951.
Timman, R. The Aerodynamic Forces on an Oscillating Aerofoil between Two Parallel Walls. M. Nijhoff (The Hague). 1951.
Timoshenko, S. and J. N. Goodier. Theory of Elasticity. 2nd edition. McGraw-Hill. 1951.
*Unesco. International Conference on Science Abstracting. Unesco. 1950.

Aeronautical Research Council. Current Papers

54—*Focusing Schlieren systems. R. W. Fish and K. Parnham.*
55—*The experimental approach to the problems of shaft whirling. E. Downham.*
56—*The incompressible potential flow past two-dimensional aerofoils with arbitrary surface suction. W. T. Lord.*
57—*Free flight measurements at supersonic speeds of the drag of a particular delta wing having a simple pressure distribution. P. J. Herbert.*

Aeronautical Research Council. Reports and Memoranda

2557—*A review of the problem of choosing a climb technique, with proposals for a new climb technique for high performance aircraft. K. J. Lush.*
2572—*Calculated data for the combustion with liquid oxygen of water-diluted alcohols and paraffin in rocket motors. I. C. Hutcheon and S. W. Green.*
2575—*A new method of numerical integration of the equations of the laminar boundary layer. T. G. Cowling.*
2583—*Lateral control with high lift devices. A. D. Young.*

The College of Aeronautics, Cranfield. Report

48—*Stability of the compressible laminar boundary layer with an external pressure gradient. J. A. Laurmann.*

Aeronautical Research Laboratories, Australia

Aerodynamics Notes

102—*Tests on a 3 ft. chord two-dimensional model with a modified Glas II profile. P. B. Atkins and T. S. Keeble.*
104—*The use of an auxiliary aerofoil to stabilise the flow on Glas II in the event of suction failure. R. Dengate and T. S. Keeble.*

Report

SM.170—*The response of a simple flexible aeroplane to gusts of various forms. F. H. Hooke.*

National Research Council of Canada. Report

MR-14—*An airborne recording tachometer. H. T. Stevinson and S. H. G. Connock.*

O.N.E.R.A., France. Note Technique

5—*Détermination théorique de l'écoulement d'un fluide derrière une onde de choc détachée. H. Cabannes.*

National Advisory Committee for Aeronautics
***Technical Notes**

2440—*Wind-tunnel investigation and analysis of the effects of end plates on the aerodynamic characteristics of an unswept wing. D. R. Riley.*

2441—*Optical methods involving light scattering for measuring size and concentration of condensation particles in supercooled hypersonic flow. E. J. Durbin.*

2442—*A photoelastic investigation of stress concentrations due to small fillets and grooves in tension. M. M. Frocht.*

2443—*The similarity law for hypersonic flow about slender three-dimensional shapes. F. M. Hamaker, S. E. Neice and A. J. Eggers, Jr.*

2444—*Effect of stress-solvent crazing on tensile strength of polymethyl methacrylate. B. M. Axilrod and Martha A. Sherman.*

2446—*Width of Debye-Scherrer lines for finite spectral width of primary beam. H. Ekstein.*

2447—*Statistical fluctuation of intensity in Debye-Scherrer lines due to random orientation of crystal grains. H. Ekstein.*

2450—*Method of matching components and predicting performance of a turbine-propeller engine. A. T. Sutor and M. A. Zipkin.*

2454—*Jet-boundary corrections for complete and semispan swept wings in closed circular wind tunnels. J. C. Sivells and Rachel M. Salmi*

2455—*A method of designing turbomachine blades with a desirable thickness distribution for compressible flow along an arbitrary stream filament of revolution. Chung-Hua Wu and C. A. Brown.*

2456—*Analytical method for determining performance of turbojet-engine tailpipe heat exchangers. M. Behun and H. C. Chandler, Jr.*

2457—*Air forces and moments on triangular and related wings with subsonic leading edges oscillating in supersonic potential flow. C. Watkins.*

2458—*An instrument employing a coronal discharge for the determination of droplet-size distribution in clouds. R. J. Brun J. Levine and K. S. Kleinknecht.*

2460—*Formation of sulfide films on steel and effect of such films on static friction. Erva C. Levine and M. B. Peterson.*

2461—*Analysis of pure-bending flutter of a cantilever swept wing and its relation to bending-torsion flutter. H. J. Cunningham.*

2462—*Influence of refraction on the applicability of the Zehnder-Mach interferometer to studies of cooled boundary layer. M. R. Kinsler.*

2464—*Two axial-symmetry solutions for incompressible flow through a centrifugal compressor with and without inducer vanes. G. O. Ellis, J. D. Stanitz and L. J. Sheldrake.*

2466—*A general correlation of temperature profiles downstream of a heated-air jet directed perpendicularly to an air stream. E. E. Callaghan and R. S. Ruggeri.*

2471—*Unsteady laminar boundary-layer flow. F. K. Moore.*

2476—*An empirical method permitting rapid determination of the area, rate, and distribution of water-drop impingement on an airfoil of arbitrary section at subsonic speeds. N. R. Bergrun.*

2480—*Comparison of heat transfer from airfoil in natural and simulated icing conditions. T. F. Gelder and J. P. Lewis.*

2490—*Flight investigation of some factors affecting the critical tail loads on large airplanes. H. H. Brown.*

2491—*Kinetics of sintering chromium carbide. W. G. Lidman and H. J. Hamjian.*

2492—*A method of solving the direct and inverse problem of supersonic flow along arbitrary stream filaments of revolution in turbomachines. Chung-Hua Wu and Eleanor L. Costilow.*

2494—*Lift and moment on oscillating triangular and related wings with supersonic edges. H. C. Nelson.*

2498—*Flight investigation of the effect of atmospheric turbulence on the climb performance of an airplane. H. Press and H. C. McClanahan, Jr.*

2500—*A comparison of the turbulent boundary-layer growth on an unswept and a swept wing. J. M. Altman and Nora-Lee F. Hayter.*

2502—*Examples of three representative types of airfoil-section stall at low speed. G. B. McCullough and D. E. Gault.*

Civil Aeronautics Administration, Indiana, U.S.A.

Technical Development Report No. 144—*The load transmission test for flexible paving and base courses. Part II. Triaxial test data on structural properties of granular base materials. W. M. Aldous, R. C. Herner and M. H. Price.*

University of Washington Engineering Experiment Station, U.S.A.

Bulletin No. 118—*Investigations in aeronautics. R. M. Rosenberg (Editor).*

Bulletin No. 119—*The extremum principles of the mathematical theory of elasticity and their use in stress analysis. W. Prager.*

APPOINTMENTS

This page of the JOURNAL is available for advertisements of appointments in the Industry, the Ministries, Universities and Colleges. The charge for advertisements for each inch, or part of an inch, in depth is £2 10s. 0d.

THE ENGLISH ELECTRIC CO. LTD., LUTON, have the following vacancies on guided weapon projects:—**Research Engineer** (Ref. 441C) for work on planning and analysis of supersonic flight tests. Applicants should have a degree, H.N.C. or equivalent qualification. Previous experience of stability and control work an advantage. **Aerodynamics Engineer** (Ref. 457B) with degree in aeronautical engineering for work on supersonic aerodynamics. A good knowledge of mathematics particularly calculus is essential. Previous experience in Industry not necessary. **Structural Engineer** (Ref. 845A) as assistant on structural research and design on supersonic project. H.N.C. or recognised diploma in appropriate subjects. Practical experience in design and stressing of aircraft structures an advantage. Applications stating age, technical qualifications and experience to Central Personnel Services, 24 Gillingham Street, London, S.W.1, quoting appropriate reference.

PLANNING ENGINEERS required by large Aircraft firm in the Midlands engaged on attractive and progressive programme of work. Previous aircraft experience desirable, but not essential. Interviews will be arranged locally where possible. Apply stating age, experience, and salary to Box. 215.

APPLICATIONS are invited for the following positions in the AIRCRAFT DIVISION of the English Electric Co. Ltd., at Warton Aerodrome, near Blackpool:—1. **Engineer** for the design and development of a new supersonic wind tunnel project. Applicants should have good experience of this type of work. Degree or equivalent preferred (Ref. 952). 2. **Engineer** for flight test liaison with the South of England. Applicants should have technical experience in the Aircraft Industry and have an honours degree in engineering or its equivalent (Ref. 953). 3. **Engineers** for aero-elastic and allied investigations. Applicants should have aerodynamic or structural training and experience (Ref. 435G). 4. **Engineer/Mathematician** for investigations into mechanical methods for aerodynamic and allied calculations. Applicants should be Graduates of first class mathematical ability (Ref. 954). Please write giving full details and quoting appropriate reference to English Electric Company Ltd., Central Personnel Services, 24/30 Gillingham Street, London, S.W.1.

ASSISTANT CHIEF DESIGNER required, age 30-40, salary £1,000-£1,500 according to qualifications. Applicant should have First or Second Class Honours Degree in Mechanical Engineering and have practical experience to A.M.I.Mech.E. standard. Experience should cover organisation and administration of an aircraft equipment design office. Preliminary interview London.—Apply Box 186.

APPLICATIONS are invited by the **MINISTRY OF SUPPLY** for a post in the grade of **PRINCIPAL SCIENTIFIC OFFICER** at London Headquarters. Duties include assistance in the formulation, co-ordination and progressing of the research and development programme in Industry and at Government Establishments in connection with propulsive units for guided weapons. It will be necessary also to study future trends, compile broad specifications for projected units, to define detailed official requirements and to check that these are met. Candidates, who must be at least 31, should have a 1st or 2nd class honours degree in Mathematics, Physics or Engineering or equivalent qualification with a good knowledge of thermo-dynamics and also, preferably, of aerodynamics and/or combustion. Experience of research, design or development work connected with propulsive units for aircraft work such as turbo-jets or rocket motors is highly desirable. Salary will be assessed according to qualifications and experience, within the range £1,000 to £1,375. Rates for women somewhat lower. The post is unestablished but carries benefits under F.S.S.U. Application forms obtainable from the Ministry of Labour and National Service, Technical and Scientific Register (K), Almack House, 26-28 King Street, London, S.W.1, quoting Ref. C706/51A. **Closing date, 2nd February, 1952.**